NOAA Technical Memorandum NMFS

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JULY 1990

ATLAS OF EASTERN TROPICAL PACIFIC OCEANOGRAPHIC VARIABILITY AND CETACEAN SIGHTINGS, 1986-1989

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NOAA Technical Memorandum NMFS

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INTRODUCTION

The National Marine Fisheries Service, Southwest Fisheries Center, is conducting a six-year progam to estimate trends in relative abundance of dolphin stocks affected by the tuna purse-seine fishery in the eastern tropical Pacific Ocean (ETP). Two NOAA ships, the David Starr Jordan and the McArthur, surveyed a study area covering the range of target species from late July through early December each year. Environmental variables are monitored along the cruise track to study relationships between environmental variability and cetacean distributions in order to interpret changes in abundance estimates.

This report presents four years of daily oceanographic and sighting data collected continuously along the cruise tracks. Continuous surface temperature, salinity, and chlorophyll concentration data show small-scale habitat variability on scales of 1-100 km. Subsurface temperature sections based on 4-10 XBT casts per day are also presented. The surveys cover the ranges of five "target species" most affected by the fishery: spotted dolphin (*Stenella attenuata*), spinner dolphin (*S. longirostris*), striped dolphin (*S. coeruleoalba*), common dolphin (*Delphinus delphis*), and Fraser's dolphin (*Lagenorhynchus hosei*). All cetacean species that are sighted are recorded. Cetacean sightings are plotted with the along-track oceanographic data to allow a preliminary assessment of species-environment relationships. Patterns in the distribution and abundance of cetaceans relative to oceanographic variability can be discerned in the data. Quantitative analysis of these patterns could be used to help interpret interannual changes in abundance estimates and in ecological studies of certain species. Larger-scale patterns of oceanographic variability during 1986-1988, based on XBT and station hydrocast data, have been presented by Fiedler *et al.* (1990). Associations between these patterns and dolphin distribution in 1986 and 1987 have been presented by Reilly (1990).

OCEANOGRAPHY OF THE ETP

The oceanography of the eastern tropical Pacific has been described in detail elsewhere (Wyrtki 1966, 1967; Fiedler 1990, Fiedler *et al.* 1990) and will be reviewed briefly here. Figure 1 shows a schematic diagram of the large-scale surface currents and water masses of the region. The general features of the surface current system can also be deduced from the average thermocline topography, shown in Figure 2 for the months of August-November. The 20°C isotherm is found in the middle of the thermocline and its depth is used to represent thermocline depth in the tropical Pacific (Donguy and Meyers, 1987). We use the traditional names of ridges and troughs in sea level or dynamic height (Wyrtki, 1974) to label the corresponding subsurface troughs and ridges in the thermocline topography, as did Kessler (1990).

In accordance with simple geostrophic theory, the spatial variations of the depth of the thermocline reflect the directional tendencies of the largely zonal, near-surface currents of the ETP. In the northern hemisphere the thermocline will be deeper to the left of a current as the observer looks downstream, while in the southern hemisphere the opposite is true. Thus, the broadest current in the ETP, the South Equatorial Current (SEC), flows westward through the region, extending in the cross-stream direction from the southern edge of the ETP across the equator to almost 5N. North of the countercurrent thermocline ridge at 10N, where the thermocline slopes downward to the north, the North Equatorial Current (NEC) also flows westward. Along the eastern boundary, the thermocline slopes upward toward the coasts of Peru and Baja California, reflecting the equatorward flow of the Peru and California Currents. These coastal systems feed into the eastern, "upstream" ends of the NEC and SEC.

Between the NEC and SEC, on the southern flank of the countercurrent thermocline ridge, the North Equatorial Countercurrent (NECC) flows eastward. The NECC shows considerable seasonal variation, being strongest during November-December when the slope of the thermocline ridge is steepest (Kessler and Taft, 1987). These variations can be largely explained by local Ekman dynamics. The NECC lies beneath the Intertropical Convergence Zone (ITCZ) where the northeast and southeast tradewinds converge. As the ITCZ migrates from its northern extreme in late summer to its southern extreme in late winter, the curl of the wind-stress over the ridge changes from cyclonic (causing Ekman upwelling of the ridge) to anticyclonic (causing downwelling of the ridge). The phase and amplitude of the variations in the curl are sufficient to account for the variations in the depth of the thermocline ridge and the strength of the NECC (Meyers, 1979; Kessler and Taft, 1987). The shallow eastern end of the countercurrent thermocline ridge is the Costa Rica Dome at 10N, 90W (Wyrtki, 1964).

There are three principal surface water masses in the ETP (Wyrtki, 1966, 1967). The Equatorial Surface Water (ESW) is the tongue of cool, moderately saline water which appears to extend westward along the equator from the Peruvian coast (Figure 2). Conflicting theories suggest that the average state of the cold tongue is maintained either by equatorial upwelling and advection of cold water from the Peru Current by the SEC (Wyrtki, 1981) or by the eastward advection cold water by the Equatorial Undercurrent as it rises to the surface near 95W (Bryden and Brady, 1987). Whichever mechanism may be correct for the average state, advection of water by the SEC may play an important role in variations of sea surface temperature (SST) in the cold tongue (cf. Leetmaa, 1983). Observations show that annual variations in SST are larger near the coast and that the phase of the variations propagates westward from the coast (Horel, 1982). Thus, the coldest SSTs realative to the annual mean occur in August-September near the coast while at 140W, for example, the coldest SSTs occur in November.

Toward the poleward edges of the ETP, cool, high-salinity Subtropical Surface Water (SSW) is found in the subtropical gyres of the North and South Pacific. Annual variations in these regions simply reflect the seasons: SSTs are generally warmest during the summer seasons of the respective hemispheres (Horel, 1982). Embedded between the ESW and the SSW of the northern hemisphere, at about 10N, is the relatively warm and fresh Tropical Surface Water (TSW). The TSW lies beneath the Intertropical Convergence Zone (ITCZ) in the region of the NECC. The annual variation in SST in this region is less than the variation in the cold tongue and roughly opposite in phase, being coldest in late spring and warmest in late summer (Horel, 1982). The phase of these variations suggests that they are more likely to be caused by variations in local heating than by variations in the advection of warm water from the west by the NECC.

The Equatorial Front is a strong temperature gradient at the boundary between Tropical and Equatorial Surface Water. This front is strongest east of the Galapagos. To the west, it is typically deformed by cusp-shaped long waves with a wavelength of ~1000 km and a period of ~30 days (Philander *et al.* 1985). These waves are do not appear in the climatological surface temperature field. In addition to the three oceanic surface water masses, coastal water masses containing cold, recently upwelled water and the cool, low-salinity water of the eastern boundary curents of Peru and California are also present.

METHODS

Continuous along-track data consist of surface temperature, salinity, and chlorophyll. Surface temperature and salinity were measured by a thermosalinograph (ODEC Model TSG-102, Inter-Ocean Model 541, or Seabird SEACAT 21)[1]. Surface chlorophyll was estimated from *in vivo* fluorescence measured with a Turner Designs fluorometer. In 1986, data were recorded on strip-chart recorders and subsequently digitized. Beginning in 1987, data were recorded at 2-min intervals on a data acquisition system consisting of an AI08 board (Industrial Computer Source) connected to an IBM PC compatible microcomputer (Holland 1989). The Jordan's thermosalinograph was not interfaced with the PC in 1987, so temperature and salinity data recorded at 5-min intervals were obtained from the ship's CAMAC/Molecular data acquisition system.

Temperature data were corrected for a small bias, representing the difference between surface temperature and temperature at the depth of the seawater intake, using bucket temperatures. We felt that the precision of bucket temperature observations was not sufficient to allow correction of temporally or spatially varying errors in the thermosalinograph temperature data, i.e. these data were more precise than the bucket temperature readings. Salinity data were corrected for constant or temperature-dependent biases when discrete salinity analyses were available. Although the accuracy of the thermosalinograph salinity data could not always be improved by such corrections, the patterns of small-scale variability presented here are still valid.

The measurement of *in vivo* fluorescence and conversion to chlorophyll concentration followed the method of Smith *et al.* (1981). Ideally, the methodology includes measurement of the fluorescence of an appropriate blank at least once per day and extraction and analysis of discrete pigment samples for calibration at least six times per day. In 1986, blank fluorescence was not measured and had to be estimated using a model of the measured fluorescence signal and observed responses to changes in fluorometer gain. No continuous chlorophyll data are available from 1987: sensitivity of the fluorometer on the Jordan was set too low and the fluorometer on the McArthur was flooded soon after the start of the cruise. We plot discrete sample values instead. In 1988, adequate blanking and calibration were carried out, but the data are still contaminated by problems with variations in flow rate of seawater through the fluorometers and rust in the McArthur's seawater system. By 1989, we feel that most of the potential errors in measuring *in vivo* fluorescence had been eliminated. Thus, although the accuracy of the continuous chlorophyll data may be suspect, all or most of the small-scale variability in the data is real.

Expendable bathythermographs (XBTs) were deployed at least four times per day in water deeper than 500m. The frequency of deployment was increased in areas of special interest when supplemental probes were available.

For the cetacean census, each vessel had two teams consisting of three observers each. Teams stood alternate two-hour watches. Two observers from the team on duty used 25X binoculars to search from directly ahead to abeam of each side of the ship. The third observer served as data recorder and searched directly ahead of the ship when not recording data. Each team member spent approximately equal time at each of these duty stations.

Under ideal conditions, cetaceans could be sighted as far as 11 km perpendicular distance (pdd) from the trackline. Data used in this analysis include all on-effort sightings in Beaufort states 0-6. When possible, schools were approached and observers recorded independent "best" esimates of school size and species composition. In some cases, an observer recorded a "minimum" estimate, but could not provide a best estimate. Observer esimates were averaged to obtain mean minimum and best estimates. Cetacean sighting methods and data are described in detail elsewhere (Holt and Sexton 1987, 1988, 1989; Holt and Jackson 1987, 1988; Sexton *et al.* 1989; Hill *et al.* 1990a,b).

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[1]Reference to trade name does not imply endorsement by NMFS.

RESULTS

Weekly plots of oceanographic data and cetacean sightings are presented in the Appendix. A brief interpretation of some of the patterns in the plots follows.

JORDAN 1986

Leg 1: 31 July - 26 August 1986 (pp. 16-19)
Surface temperature and salinity gradually increased, and the thermocline deepened, as the ship left California Current Water and entered Tropical Surface Water during 31 July - 7 August. Oceanographic variability was low until the ship crossed the Equatorial Front and entered Equatorial Surface Water on 14 August. No dolphins were sighted in this water. The front was crossed again as the ship re-entered Tropical Surface Water on 15 August. Very warm water off the coast of southern Mexico was encountered at the end of this leg. The fluorometer data collected on this leg could not be used.

Leg 2: 2-29 September 1986 (pp. 20-23)
Little oceanographic variability was encountered in Tropical Surface Water during 2-8 September. The ship sailed over the countercurrent thermocline ridge on 9-11 September and crossed the Equatorial Front into Equatorial Surface Water on 13 September. Chlorophyll was elevated in this water. The pronounced weakening of the thermocline during the night of 18-19 August is associated with the Equatorial Undercurrent. The ship crossed a weak Equatorial Front into Tropical Surface Water on 20 August. The Costa Rica Dome, marked by a very shallow thermocline and elevated chlorophyll levels, was encountered on 22-24 September.

Leg 3: 5 October - 1 November 1986 (pp. 24-27)
The ship sailed back and forth over the countercurrent thermocline ridge on 6-7, 9-10, 12-13, and 16-18 October. Few cetaceans were sighted on the south side of the ridge, in the North Equatorial Countercurrent (7-9 and 13-16 October). The ship sailed near the western edge of the Costa Rica Dome on 21 October, when a shallow thermocline and abundant striped dolphins were encountered. Equatorial Surface Water was encountered briefly on 24 October, north of the Galapagos. The ship crossed a strong salinity front and entered coastal waters in the Gulf of Panama on 28 October. Whales were abundant in this area.

Leg 4: 8 November - 5 December 1986 (pp. 28-31)
The ship crossed a strong salinity front into Tropical Surface Water on 9 November. The ship touched the Equatorial Front north of the Galapagos during the night of 11-12 November. Many spinner and spotted dolphins were sighted here. The ship returned to and stopped at the Galapagos on 17-18 November. After this stop, the ship was in Tropical Surface Water on 19-20 November. It then re-entered Equatorial Surface Water, perhaps in the cusp of an equatorial long wave, crossing the Equatorial Front on 21 November. The ship was back in Tropical Surface Water by 24 November and sailed over the countercurrent thermocline ridge on 28-29 November. Sightings began to increase when the ship entered cooler, less stratified coastal water off Baja California on 2 December.

McARTHUR 1986

Leg 1: 30 July - 26 August 1986 (pp. 32-35)

The thermosalinograph was inoperative during this leg. The XBT temperature section shows that surface temperature increased and the water column became more stratified as the ship sailed from California Current Water to Tropical Surface Water on 1-5 August. The ship sailed over the countercurrent thermocline ridge on 5-6 August and crossed the Equatorial Front on 8 August. The ship remained in Equatorial Surface Water until 26 August, when it entered colder Ecuadorean coastal water where cetaceans were abundant. The weakening of the thermocline on 22 August may indicate a mesoscale, subsurface eddy.

Leg 2: 4-30 September 1986 (pp. 36-39)

The ship was in Peru Current water until 8 September, when it entered Equatorial Surface Water. The ship sailed along the equator, over the Equatorial Undercurrent, during 14-16 September. A patch of warm, low-salinity water was crossed on 15 September. Striped dolphins were abundant at the edge of this patch. As the ship made an unscheduled transit to Panama on 18-20 September, surface temperature increased and salinity decreased as it left Equatorial Surface Water. For the last week of this leg, the ship remained mostly in the Gulf of Panama, although it entered Equatorial Surface Water, and encountered many common dolphins, on 25 September.

Leg 3: 5 October - 1 November 1986 (pp. 40-43)

The ship crossed through cool, high-salinity Equatorial Surface Water south of the Galapagos on 9-11 October, when many cetaceans were sighted. After re-entering Tropical Surface Water, surface temperature and salinity gradually increased and chlorophyll gradually decreased as the ship sailed into Subtropical Surface Water on the way to Hawaii. The salinity excursions on 14, 25, and 26 September are probably spurious. No XBT's were deployed after 23 October on this leg due to a computer failure.

Leg 4: 8 November - 5 December 1986 (pp. 44-47)

The thermocline strengthened and shoaled as the ship sailed from Subtropical to Tropical Surface Water during 9-13 November. The ship sailed over the countercurrent thermocline ridge on 14-15, 18, and 27 September. The ship skirted the Equatorial Front on 23-24 November. The chlorophyll patch and weak front crossed on 30 November and 1 December may be associated with the Islas Revillagigedo. The ship entered cool, low-salinity, weakly-stratified California Current Water along the coast of Baja California on 2 December. Common dolphins, and then striped dolphins, were abundant here.

JORDAN 1987

Leg 1: 8-28 August 1987 (pp. 48-50)

Surface temperature and salinity increased and the water column became more stratified as the ship left California Current water during 8-12 August. Salinity decreased again as the ship entered warm Tropical Surface Water, marked by a moderate temperature front on 13 August. The countercurrent thermocline ridge, crossed on 14-15 and 17-18 August, was deeper than normal during El Niño 1987 (Fiedler *et al.* 1990). Very warm surface water was encountered along the coast of southern Mexico during 22-27 August.

Leg 2: 5 September - 2 October 1987 (pp. 51-54)

The ship encountered very warm Tropical Surface Water on 7-8 September, then sailed over the countercurrent thermocline ridge on 10-11 September. Although bad weather stopped sighting effort on 10-11 September, virtually no cetaceans were sighted during 12-14 September when effort resumed. The subsurface temperature structure on 13 September indicates an cyclonic, cold-core eddy. The ship crossed the Equatorial Front into Equatorial Surface Water on 19 September, and then recrossed the front back into Tropical Surface Water on 22 September. Two large schools of spotted and spinner dolphins were sighted on the warm side of this front. The ship sailed near the Costa Rica Dome on 26-27

September. The Dome was not apparent in the oceanographic data, but cetaceans were abundant. Thermosalinograph data were not recorded during 12-17 September when the CAMAC/Molecular system was shut down.

Leg 3: 8 October - 4 November 1987 (pp. 55-58)

The ship crossed the Costa Rica Dome on 17-18 September, as indicated by the elevated surface salinity and strong, shallow thermocline. Striped dolphins and other cetaceans were abundant in this water. The ship then sailed back and forth over the countercurrent thermocline ridge during 21-31 October. The ridge had shoaled since August, as El Niño was ending. Very warm surface water was encountered as the ship approached Manzanillo on 3-4 November.

Leg 4: 8 November - 5 December 1987 (pp. 59-62)

The ship sailed over a subsurface eddy beneath Tropical Surface Water on 10-11 November, and then along the countercurrent thermocline ridge during 13-15 November. The ship sailed near the Equatorial Front during 20-23 August, although it never clearly entered Equatorial Surface Water. After sailing over the countercurrent thermocline ridge on 24-25 November, variability in Tropical Surface Water was low until the ship began to encounter California Current water in December.

McARTHUR 1987

Leg 1: 31 July - 27 August 1987 (pp. 63-66)

Surface temperature increased and the water column became more stratified as the ship sailed from California Current water into Tropical Surface Water on about August 7. The salinity signal was abnormally noisy during the first and third weeks of this leg. The ship sailed over the countercurrent thermocline ridge on 8-9, 15, and 20 August. The ridge became stronger and shallower to the west, demonstrating the more pronounced influence of El Niño in the east. The weakened thermocline and cool surface water encountered on 18 August may indicate the influence of Subtropical Surface Water. After 20 August, surface salinity increased, surface temperature and chlorophyll decreased, and the thermocline became deeper and weaker as the ship entered Subtropical Surface Water.

Leg 2: 3-30 September 1987 (pp. 67-70)

The ship entered Tropical Surface Water and sailed over the countercurrent thermocline ridge on 5-6 September. Surface chlorophyll was elevated beginning on 16 September as the ship sailed near the Equatorial Front. The ship entered Equatorial Surface Water on 22 or 23 September, although it did not cross a strong Equatorial Front until it re-entered Tropical Surface Water on 27 September. Surface salinity decreased as the ship entered coastal water in the Gulf of Panama on 29 September.

Leg 3: 7 October - 3 November 1987 (pp. 71-74)

The ship entered Tropical Surface Water on 10 October and crossed the Equatorial Front into Equatorial Surface Water on 16 October. Surface temperature and salinity varied little and surface chlorophyll was elevated in this water. The equatorial thermocline was still depressed due to the lingering effect of El Niño. The ship crossed the Equatorial Front back into Tropical Surface Water on 29 October. Abundant striped dolphins and other cetaceans were encountered on the edge of a patch of high-salinity water in the Gulf of Panama on 2 November.

Leg 4: 10 November - 7 December 1987 (pp. 75-78)

The ship left the coastal water of the Gulf of Panama on 12 November and was in Tropical Surface Water for a day before crossing a strong Equatorial Front into Tropical Surface Water on 13 September. Striped dolphins were abundant on the cold side of this front. The ship crossed a much weaker Equatorial Front to the west on 30 November and entered Tropical Surface Water. Surface temperature decreased and the thermocline weakened as the ship entered water influenced by the California Current on 5 December.

JORDAN 1988

Leg 1: 29 July - 25 August 1988 (pp. 79-82)

Surface temperature increased, surface salinity increased and then decreased, and the thermocline strengthed as the ship sailed from California Current water into Tropical Surface Water by 5 August. The ship began to sample water influenced by Equatorial Surface Water on 7 August, when a moderate temperature-salinity-chlorophyll front was crossed. A patch of cold water, that had perhaps been detached from the Equatorial Front, was crossed on 8 August and a strong Equatorial Front was crossed on 9 August. Heading due east, the Equatorial Front was crossed again on 11 August, indicating an effect of equatorial long waves. The ship was in Equatorial Surface Water, where the thermocline was unusually shallow due to La Niña (Fiedler *et al.* 1990), from 9 to 15 August. The ship crossed the Equatorial Front again on 15 August as it entered Tropical Surface Water. The ship crossed a patch of cold water as it sailed near the Equatorial Front on 20 August, and then encountered a very strong and shallow thermocline and elevated surface chlorophyll as it entered Central American coastal waters.

Leg 2: 2-29 September 1988 (pp. 83-86)

The ship left high-chlorophyll, low-salinity coastal water on 4 September and entered Tropical Surface Water. The ship crossed the Equatorial Front heading due south on 12 September and then recrossed it obliquely on 18 September. The ship crossed the Costa Rica Dome on 22 September. Surface chlorophyll was elevated at the edges of the Dome. Surface salinity decreased as the ship entered coastal water in the Gulf of Panama on 28 September.

Leg 3: 5 October - 1 November 1988 (pp. 87-90)

The ship remained in coastal waters influenced by runoff and upwelling through 8 October and then crossed the Costa Rica Dome on 9-10 October. No striped dolphins were sighted on this crossing of the Dome, but they were abundant when the ship recrossed the Dome and remained over the eastern end of the countercurrent thermocline ridge on 14-18 August. Surface chlorophyll was elevated over this ridge until 20 August, when the ship entered more typical Tropical Surface Water and encountered abundant dolphins. Moderate variability was encountered in the water for the remainder of the leg. The XBT launcher failed on 23 October and no XBT's were deployed for the remainder of the leg.

Leg 4: 8 November - 5 December 1988 (pp. 91-94)

Cetaceans were abundant near the coast of southern Mexico during 8-11 November, until the ship moved offshore into Tropical Surface Water. The ship stopped at Clipperton Island on 13-14 November and sailed around it on 20 November. By 25 November, the ship was leaving Tropical Surface Water and detecting the influence of cooler California Current water. Surface chlorophyll was elevated near the Islas Revillagigedo on 26-27 November. Common dolphins were abundant, and chlorophyll was high, along the coast of southern Baja California on 1-3 December.

McARTHUR 1988

Leg 1: 29 July - 25 August 1988 (pp. 95-98)

Surface temperature increased, surface salinity increased and then decreased, and the thermocline strengthened as the ship left California Current water and entered Tropical Surface Water by 4 August. On 8 August, surface temperature had decreased and salinity increased as the ship sailed near Equatorial Surface Water. The ship crossed a patch of cold, saline water that may have contained equatorial water on 10 August. The ship sailed over the countercurrent thermocline ridge on 13 August. The thermocline weakened on 16-17 August as the ship approached Subtropical Surface Water. The ship was back in Tropical Surface Water during 18-21 August and then sailed through Subtropical Surface Water to Hawaii. The sudden change in subsurface temperature structure on 22 August is not well-defined due to a missing morning XBT.

Leg 2: 1-28 September 1988 (pp. 99-102)

Surface temperature increased and salinity decreased soon after the ship sailed on 1 September and entered Tropical Surface Water. The thermocline rapidly shoaled and strengthened on 2 September and the ship sailed over the countercurrent thermocline ridge on 3 September. On 6 September, the ship crossed a patch of cool, weakly-stratified water that could have been an eddy containing Equatorial Surface Water. The Equatorial Front was crossed on 12 September, after which the ship was in Equatorial Surface Water until 14 September. Then the ship crossed and recrossed the Equatorial Front several times until 16 September. On 22-23 September, as the ship approached the Galapagos, it encountered some very cold Equatorial Surface Water with high chlorophyll concentrations. This was probably the result of equatorial upwelling enhanced by island topography. After leaving the Galapagos on 26 September, the ship sailed into Tropical Surface Water before entering the Gulf of Panama.

Leg 3: 5 October - 1 November 1988 (pp. 103-106)

The ship left the low-salinity water of the Gulf of Panama on 6 October and sampled Tropical Surface Water until 12 October. On 13-14 October, surface temperature decreased and salinity increased as the ship sailed north of the Galapagos. After crossing the Equatorial Front on 16-17 October, cetacean sightings increased. On 26 October, the ship entered cold and productive Peru Current water.

Leg 4: 8 November - 5 December 1988 (pp. 107-110)

The ship left cold, high-chlorophyll Peru Current water on 10-11 November and remained in Equatorial Surface Water until 26 November. The ship crossed a cold-core eddy with elevated chlorophyll concentrations on 21 November. The ship crossed the equator, where upwelling was unusually intense, on 24-25 November. A diffuse Equatorial Front was crossed on 26 November. The ship crossed an eddy on 27 November and sailed over the countercurrent thermocline ridge on 28 November. Surface chlorophyll increased over the ridge. The ship was leaving Tropical Surface Water and sailing into California Current water on 30 November.

JORDAN 1989

Leg 1: 28 July - 26 August 1989 (pp. 111-114)

Surface temperature and salinity increased, and the thermocline strengthened, as the ship left California Current water during 31 July - 2 August. Patches of high chlorophyll, apparently in cold, upwelled water, were crossed off of southern Baja California. The ship remained in Tropical Surface Water for the remainder of the leg. Sightings (and effort) decreased considerably offshore during 14-20 August. The ship crossed the countercurrent thermocline ridge, where surface chlorophyll was elevated, on 16-17 August. Cetaceans were abundant in warm water near the coast on 24-25 August.

Leg 2: 2-29 September 1989 (pp. 115-118)

The ship was in warm coastal water, with patches of high chlorophyll, during 3-10 September. The XBT launcher was inoperative on this leg after 8 September. After a stop in Manzanillo on 11-13 September, the ship moved away from the coast, crossed a patch of Equatorial Water early on 19 September, and then crossed the Equatorial Front on 25 September. Chlorophyll increased as the ship approached the coast of Ecuador.

Leg 3: 5-25 October 1989 (pp. 119-121)

The ship crossed the Equatorial Front and entered Tropical Surface water on 7 October. On 9 October, the ship entered warm, low-salinity and high-chlorophyll water in the Gulf of Panama. Similar water was encountered off Costa Rica on 13 October. The ship crossed the countercurrent thermocline ridge on 17-19 and 21-23 October. Surface chlorophyll was elevated over the ridge. Many cetaceans were sighted in warm coastal water off Mexico.

Leg 4: 1 November - 7 December 1989 (pp. 122-126)

The ship sailed south through Tropical Surface Water and then along the countercurrent thermocline ridge on 9-15 November. The Costa Rica Dome, with high chlorophylyy and abundant striped dolphins, was encountered on 15 November. The Equatorial Front was crossed into Equatorial Surface Water on 21 November and then back into Tropical Surface Water on 22 November. After a final stop in Manzanillo, the ship returned through along the coast.

McARTHUR 1989

Leg 1: 30 July - 26 August 1989 (pp. 127-130)

No thermosalinograph data were recorded on this leg. The thermocline strengthened as the ship left California Current water and entered Tropical Surface Water during 30 July - 3 August. The Equatorial Front was crossed briefly on 9 August. The ship sailed over the countercurrent thermocline ridge on 18-20 August. The thermocline deepened and weakened as the ship left Tropical Surface Water and entered Subtropical Surface Water during 20-26 August.

Leg 2: 1-29 September 1989 (pp. 131-134)

No valid chlorophyll data were obtained on this leg. The ship left Subtropical Surface Water and sailed over the countercurrent thermocline ridge on 3-5 September. Until 22 September, the ship sailed east along the southern edge of the Tropical Surface water mass. On 11-13 and 15-17 September, the ship crossed long waves in the Equatorial Front and encountered Equatorial Surface Water. On 23-24 September, the ship encountered cold water upwelled in the lee of the Galapagos, then sailed through Equatorial Surface Water to Ecuador.

Leg 3: 6 October - 2 November 1989 (pp. 135-138)

The ship was in cold Equatorial Surface Water for most of this leg. Patches of high chlorophyll were encountered during 6-10 October. The Equatorial Front was crossed on 29-30 October as the ship sailed past the Galapagos. No cetaceans were sighted on 30 October after crossing the front.

Leg 4: 8 November - 7 December 1989 (pp. 139-142)

The ship left low-salinity coastal waters and crossed the Costa Rica Dome on 9-10 November. The ship crossed the Equatorial Front on 13 November and remained in Equatorial Surface Water until it recrossed the front obliquely on 20 November. The weakening of the thermocline on 19-20 November indicates the Equatorial Undercurrent. The ship sailed through the low-salinity Tropical Surface Water over the countercurrent thermocline ridge on 27-30 November and then began to encounter the cooler temperatures and weaker thermocline of the California Current.

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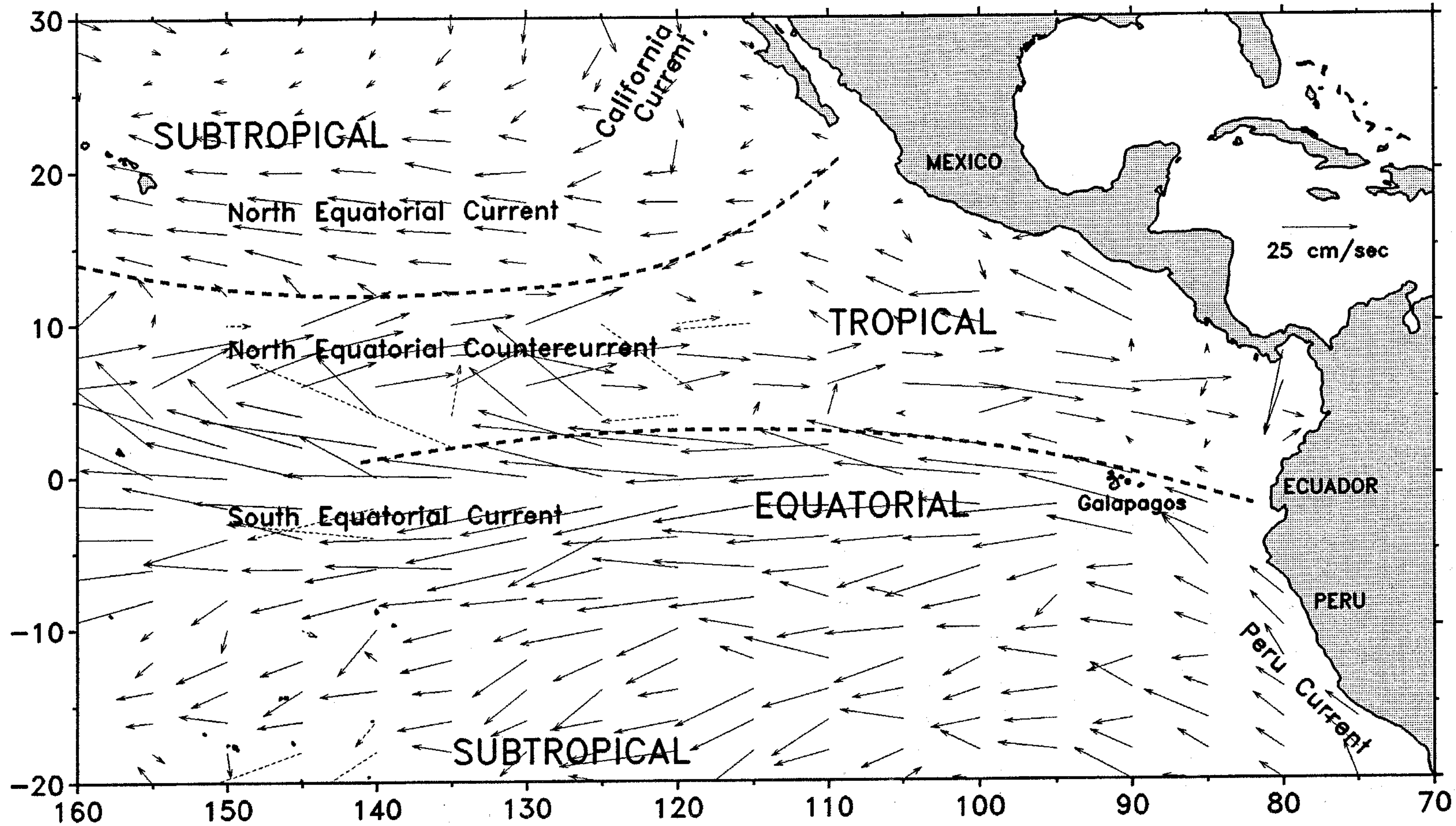


Figure 1. Eastern tropical Pacific surface currents (September-November ship drift data, Fiedler 1990) and surface water masses (Wyrtki 1967, 1968).

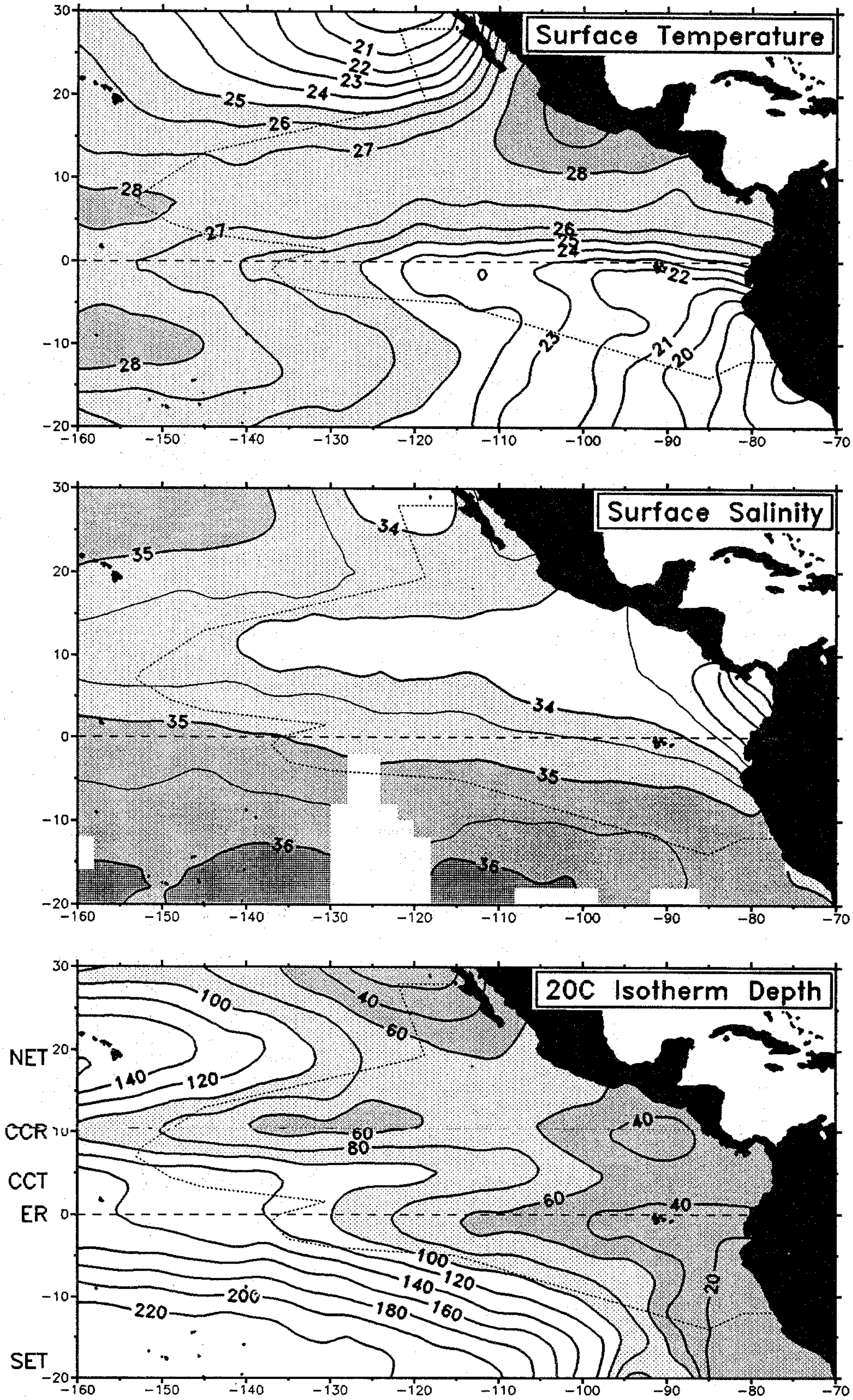


Figure 2. August-November climatological surface temperature, surface salinity, and 20°C isotherm depth. **Top:** Surface temperature, °C, n=70,700; **Middle:** Surface salinity, psu, n=8129; **Bottom:** 20°C isotherm (thermocline) depth, m, n=59,941. Thermocline topography: NET = North Equatorial Trough, CCR = Countercurrent Ridge, CCT = Countercurrent Trough, ER = Equatorial Ridge, SET = South Equatorial Trough. Dotted line = study area. Data from NODC Experimental CD-ROM NODC-01: Pacific Ocean Temperature and Salinity Profiles.

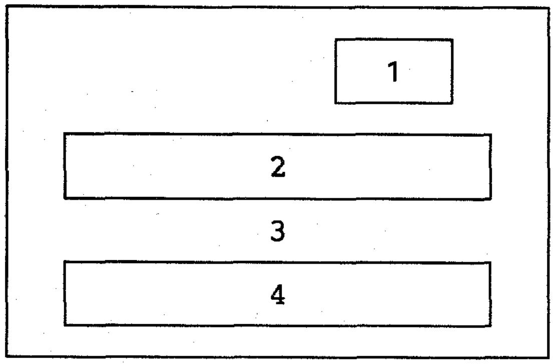
Table 1. Cetacean species (and stocks) encountered in the eastern tropical Pacific.

Letter code	Species code	Common name	Scientific name
OSD*	2	Offshore spotted dolphin	*Stenella attenuata*
SPD*	3	Spinner dolphin	*Stenella longirostris*
CD*	5	Common dolphin	*Delphinus delphis*
CSD*	6	Coastal spotted dolphin	*S. attenuata graffmani*
ESD*	10	Eastern spinner dolphin	*S. longirostris subsp. b.*
WSD*	11	Whitebelly spinner dolphin	*S. longirostris subsp. c.*
STD*	13	Striped dolphin	*Stenella coeruleoalba*
RTD	15	Rough-toothed dolphin	*Steno bredanensis*
LWB*	16	"Long-snouted whitebelly"	*Delphinus delphis subsp. ?*
SWB*	17	"Short-snouted whitebelly"	*Delphinus delphis subsp. ?*
BD	18	Bottlenosed dolphin	*Tursiops truncatus*
RD	21	Risso's dolphin	*Grampus griseus*
PWD	22	Pacific white-sided dolphin	*Lagenorhynchus obliquidens*
FD*	26	Fraser's dolphin	*Lagenorhynchus hosei*
MHW	31	Melon-headed whale	*Peponocephala electra*
PKW	32	Pygmy killer whale	*Feresa attenuata*
FKW	33	False killer whale	*Pseudorca crassidens*
PW	34	Pilot whale	*Globicephala* sp.
SPW	36	Short-finned pilot whale	*Globicephala macrorhynchus*
KW	37	Killer whale	*Orcinus orca*
SW	46	Sperm whale	*Physeter macrocephalus*
PSW	47	Pygmy sperm whale	*Kogia breviceps*
DSW	48	Dwarf sperm whale	*Kogia simus*
BW	49	Beaked whale	*Ziphiid*
SBW	50	Southern bottlenosed whale	*Hyperoodon planifrons*
UM	51	Unidentified mesoplodon	*Mesoplodon* sp.
CBW	61	Cuvier's beaked whale	*Ziphius cavirostris*
BBW	63	Baird's beaked whale	*Berardius bairdii*
RW	70	Rorqual	*Balaenoptera* sp.
MW	71	Minke whale	*Balaenoptera acutorostrata*
BRW	72	Bryde's whale	*Balaenoptera edeni*
SEW	73	Sei whale	*Balaenoptera borealis*
FW	74	Fin whale	*Balaenoptera physalus*
BLW	75	Blue whale	*Balaenoptera musculus*
HW	76	Humpback whale	*Megaptera novaeangliae*
UD	77	Unidentified dolphin	
USW	78	Unidentified small whale	
ULW	79	Unidentified large whale	
SD*	90	Spotted dolphin	*Stenella attenuata*
UC	96	Unidentified cetacean	
UW	98	Unidentified whale	

* = target species.

APPENDIX

Weekly oceanographic and sighting data are plotted as follows:



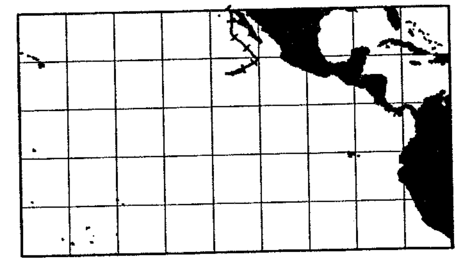
(1) Map of the 7-day cruise track, with a tick mark at 0000 hours of each day.

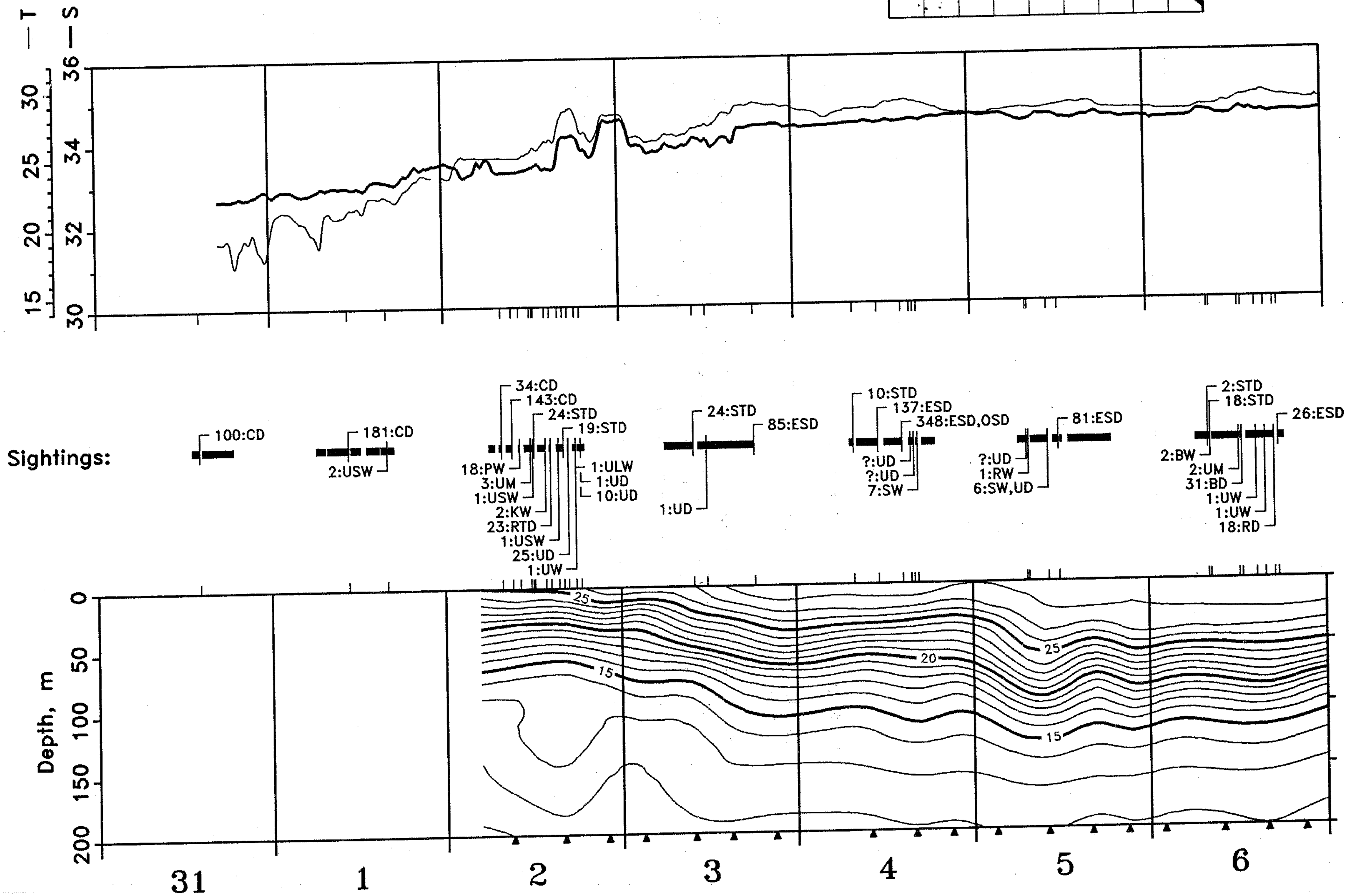
(2) Time series of surface temperature (T,°C), salinity (S, psu), and chlorophyll concentration (Chl, mg·m^{-3}).

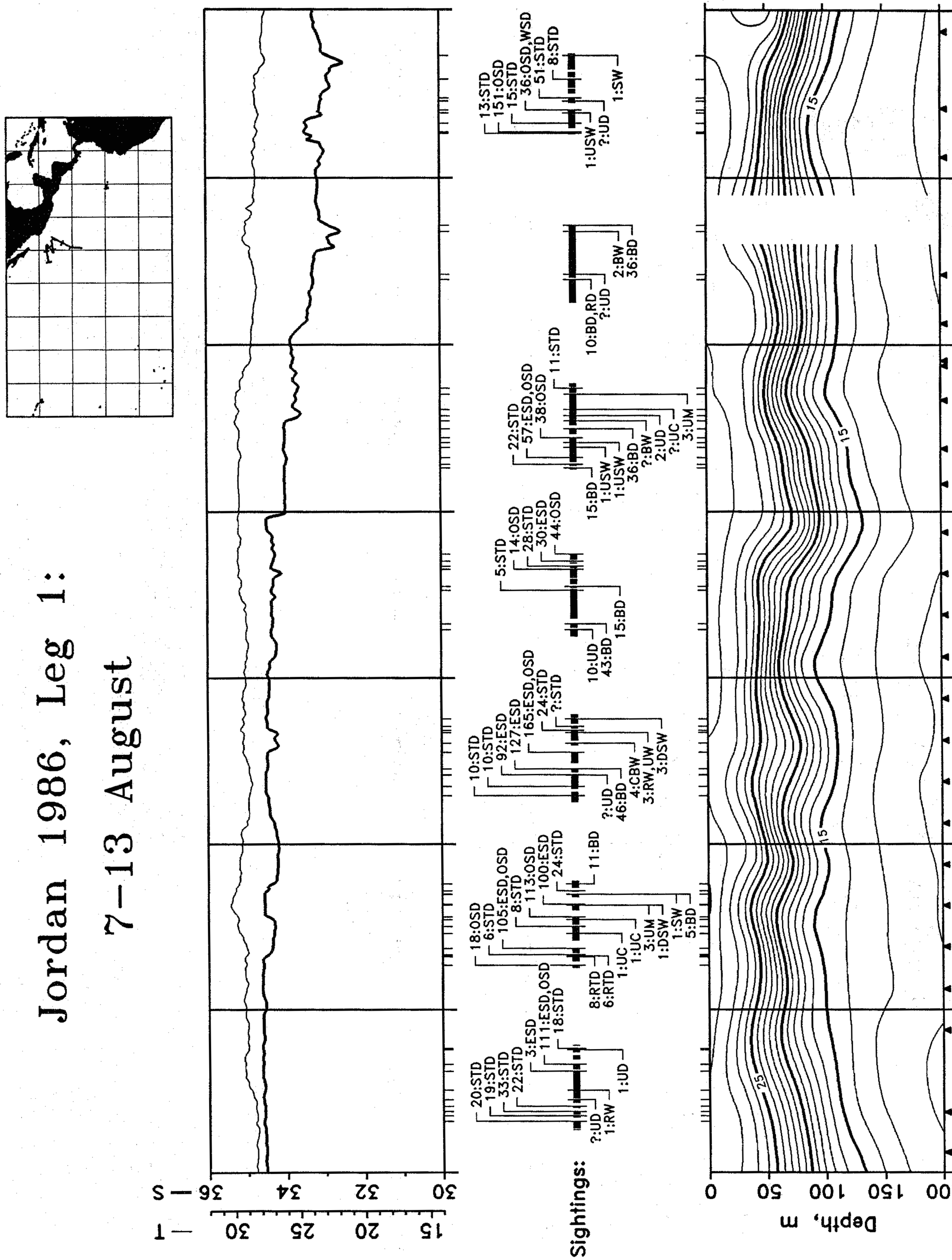
(3) Sightings (*n*:letter codes), where *n* is the mean best estimate of school size and letter codes stand for species or stock names (Table 1), plotted along bars representing sighting effort. Schools containing target species are plotted above the effort bar. Sightings are also marked by tick marks along the bottom edge of box 2 and the top edge of box 4.

(4) Temperature sections contoured from XBT profiles (marked with a ▲).

Jordan 1986, Leg 1:
31 July – 6 August

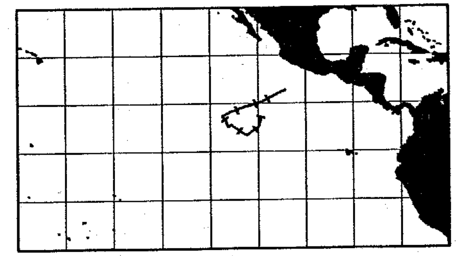


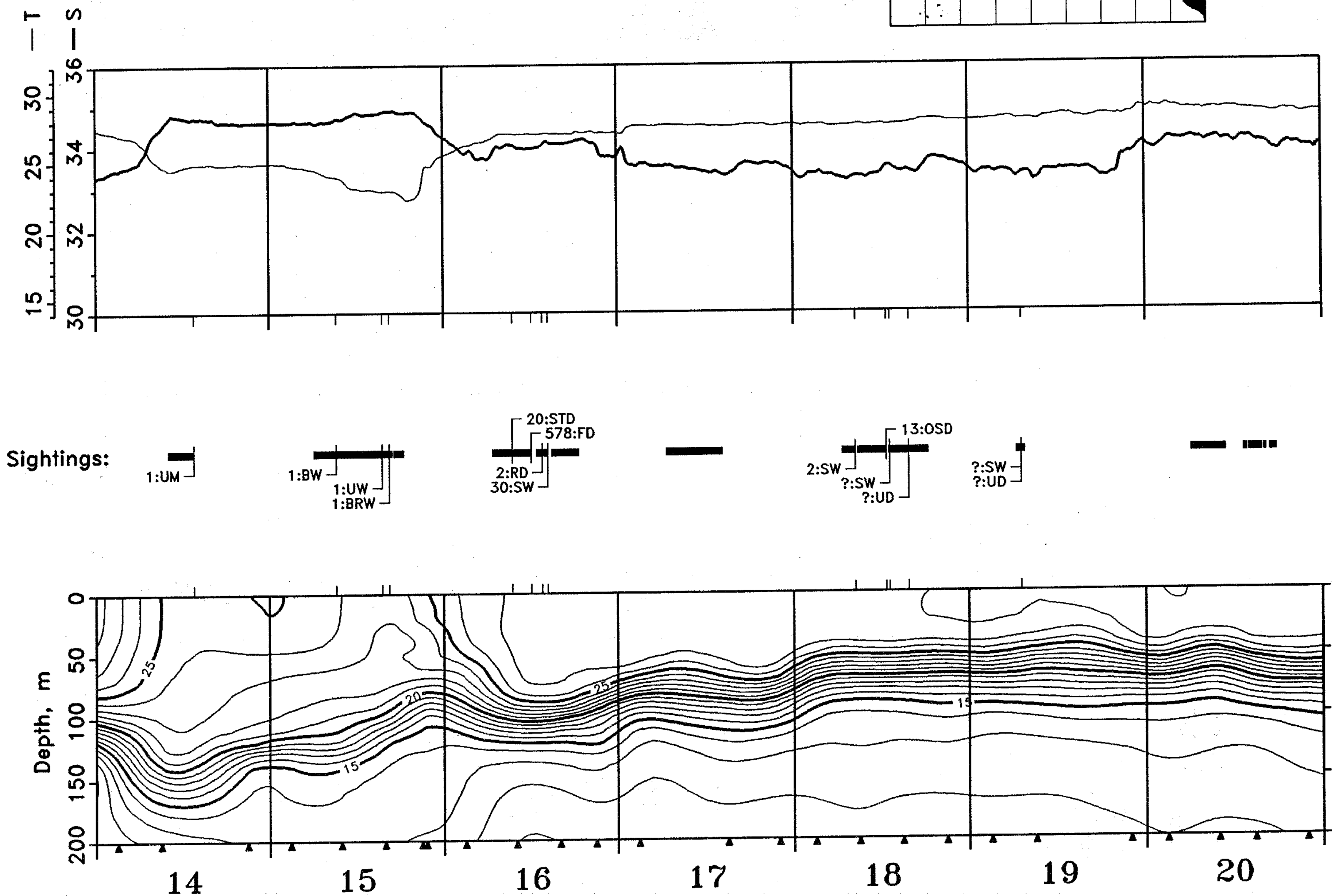




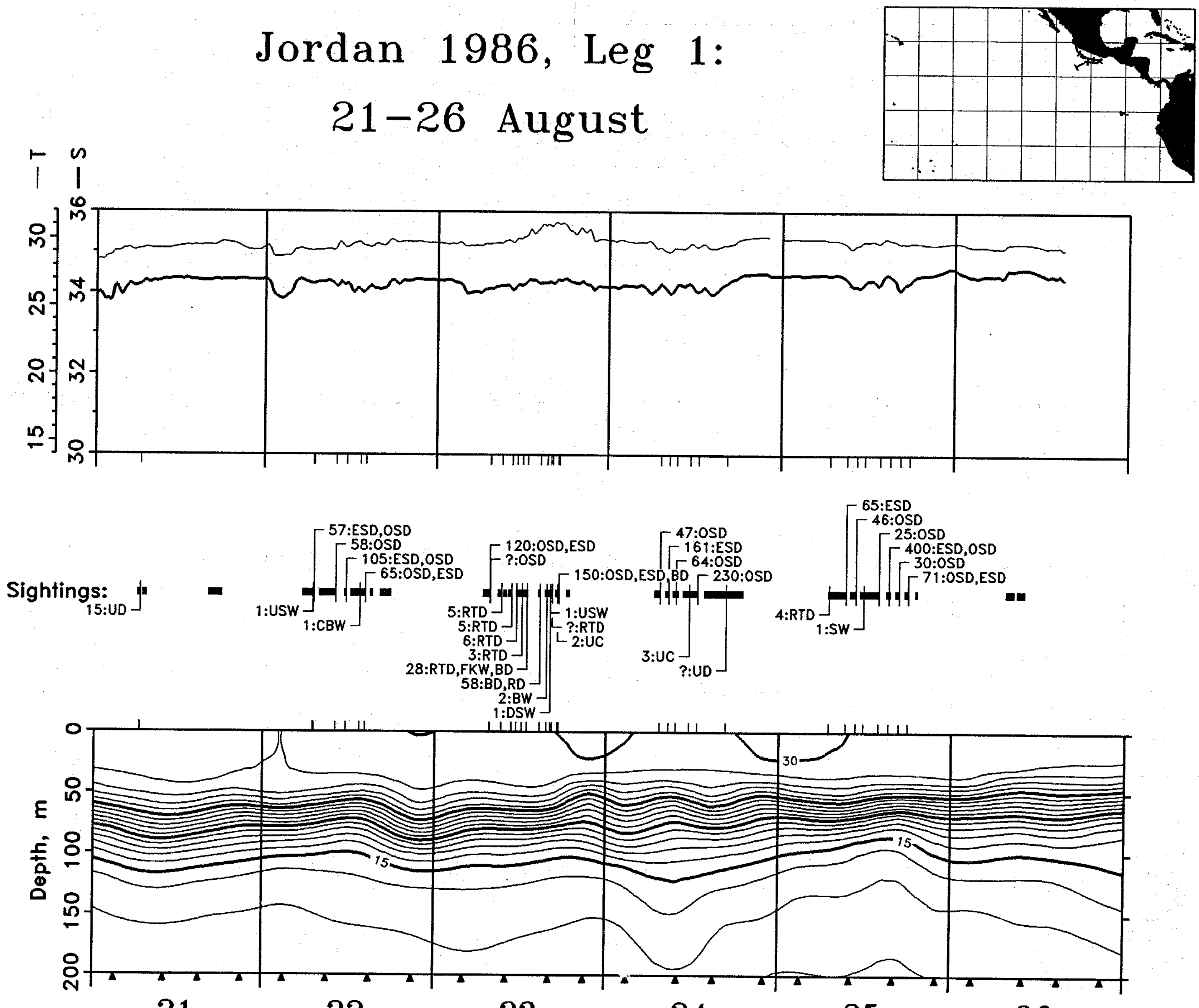
Jordan 1986, Leg 1:
7–13 August
— T
— S
36
34
32
30
30
25
20
15
Sightings:
Depth, m
0
50
100
150
200
7
8
9
10
11
12
13
15
25
20:STD
19:STD
33:STD
22:STD
3:ESD
111:ESD,OSD
18:STD
?:UD
1:RW
1:UD
18:OSD
6:STD
105:ESD,OSD
8:STD
113:OSD
100:ESD
24:STD
11:BD
8:RTD
6:RTD
1:UC
1:UC
3:UM
1:DSW
1:SW
5:BD
10:STD
10:STD
92:ESD
127:ESD
165:ESD,OSD
24:STD
?:STD
?:UD
46:BD
4:CBW
3:RW,UW
3:DSW
5:STD
14:OSD
28:STD
30:ESD
44:OSD
10:UD
43:BD
15:BD
22:STD
57:ESD,OSD
38:OSD
11:STD
15:BD
1:USW
1:USW
36:BD
?:BW
2:UD
?:UC
3:UM
10:BD,RD
?:UD
2:BW
36:BD
13:STD
151:OSD
15:STD
36:OSD,WSD
51:STD
8:STD
1:USW
?:UD
1:SW

Jordan 1986, Leg 1:
14–20 August

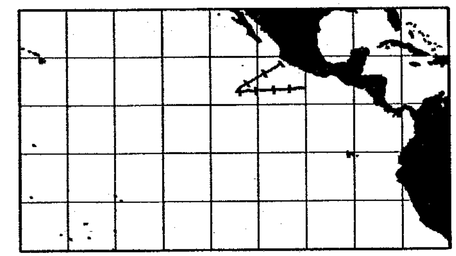


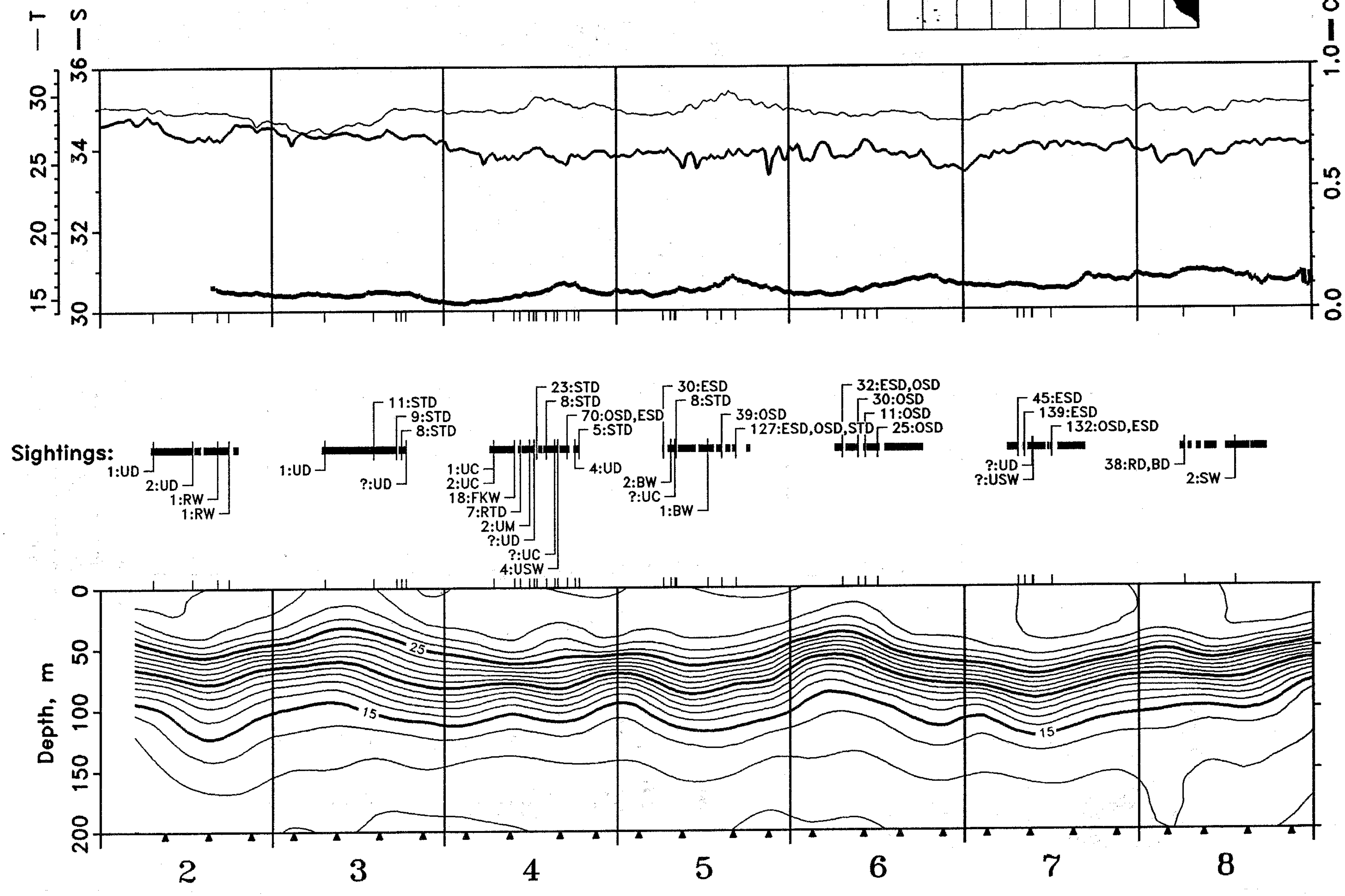


Jordan 1986, Leg 1:
21–26 August

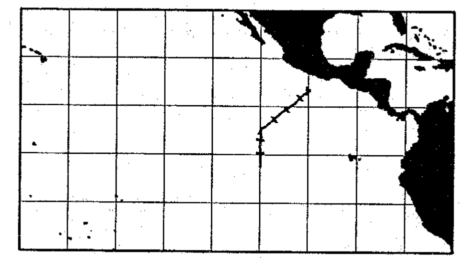


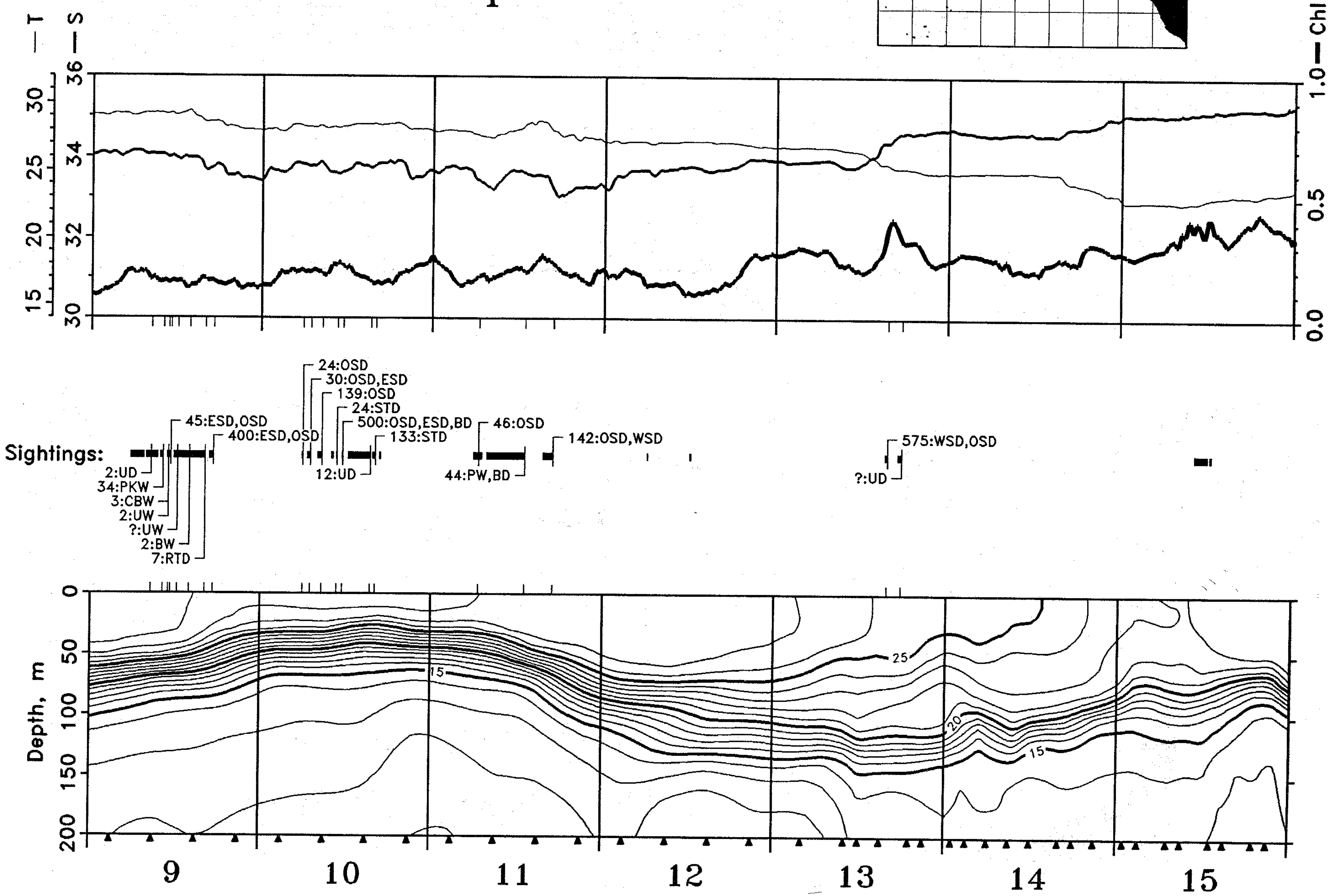
Jordan 1986, Leg 2:
2–8 September



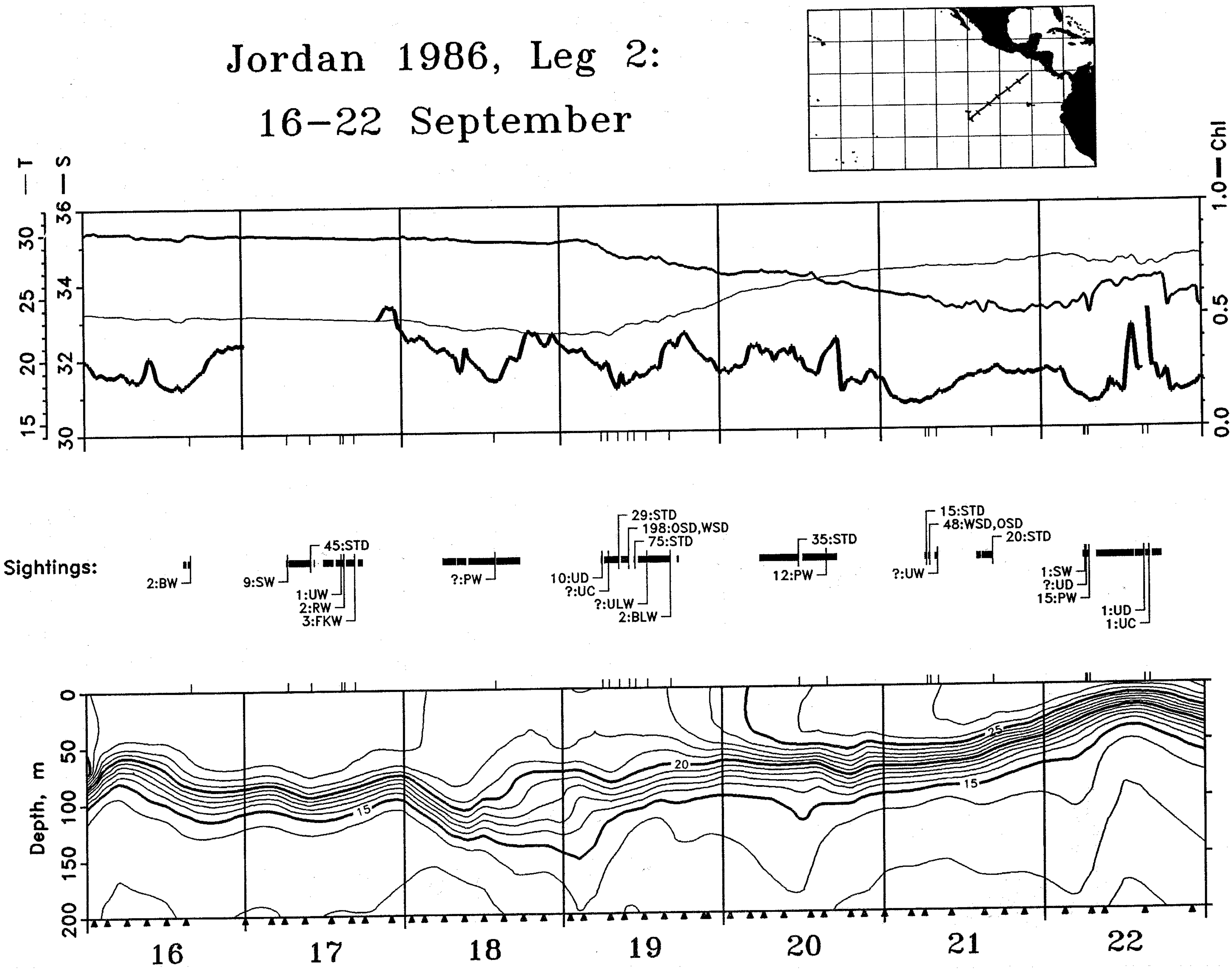


Jordan 1986, Leg 2:
9–15 September

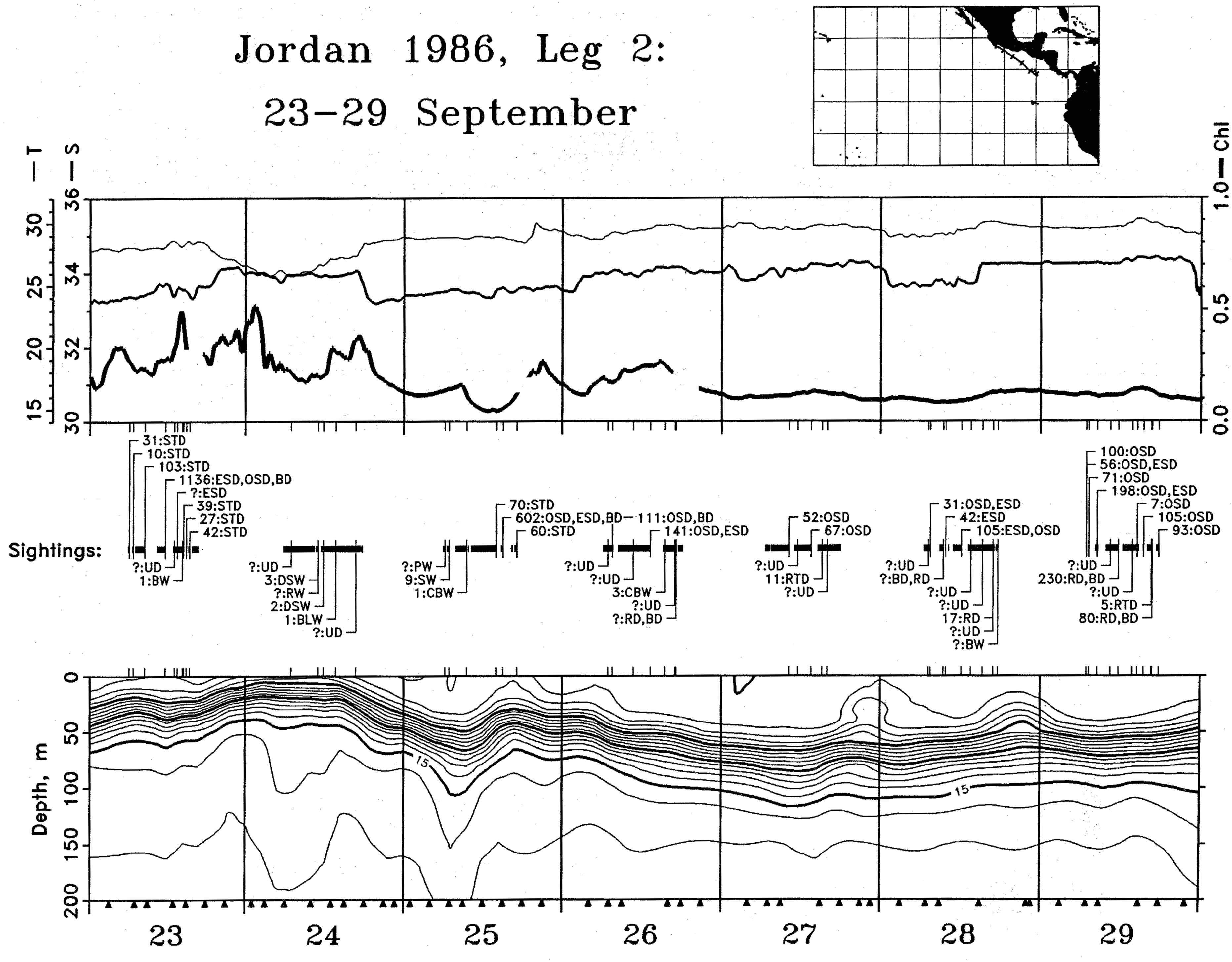




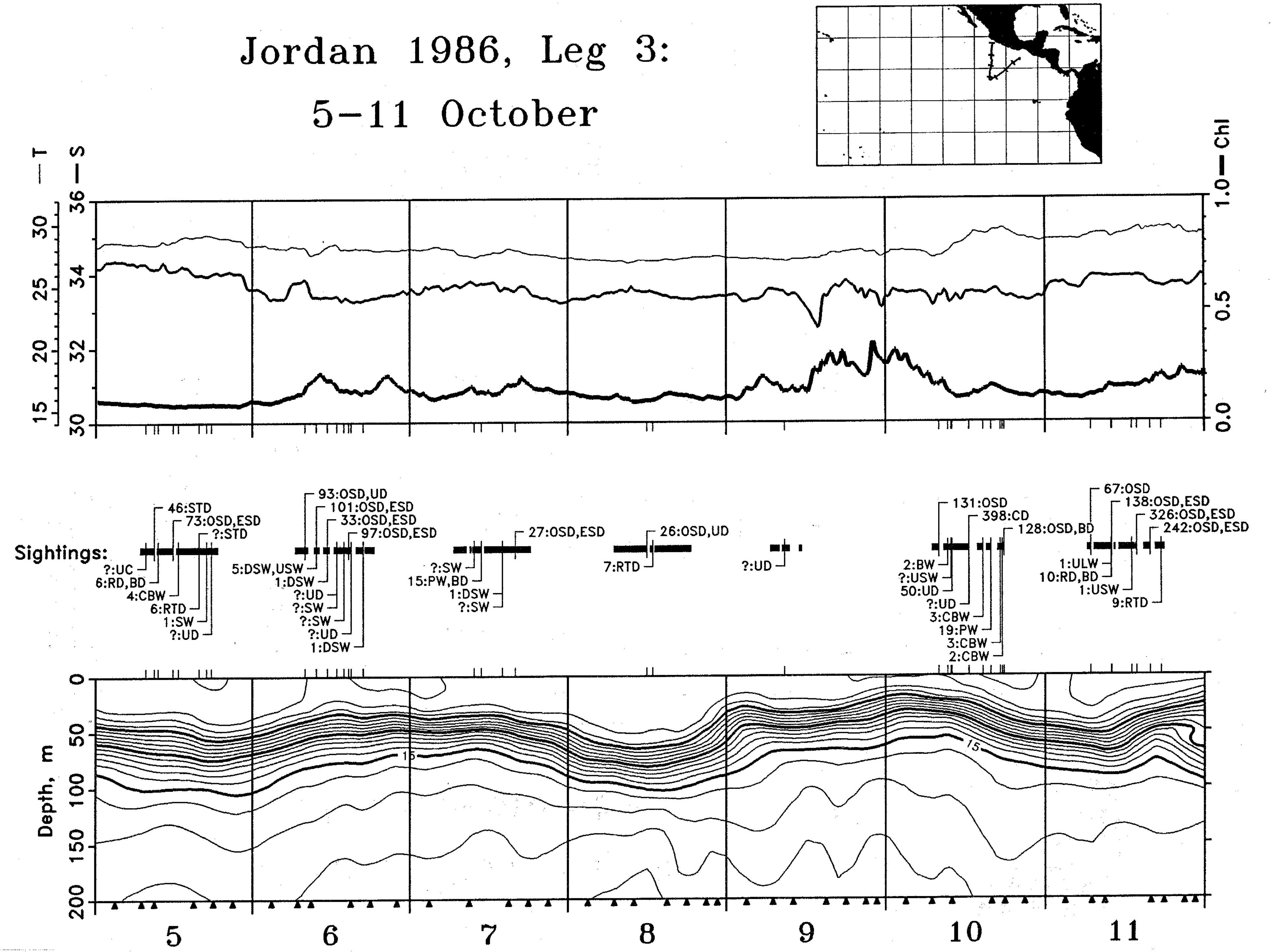
Jordan 1986, Leg 2:
16–22 September



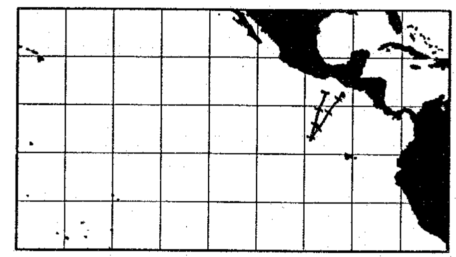
Jordan 1986, Leg 2: 23–29 September

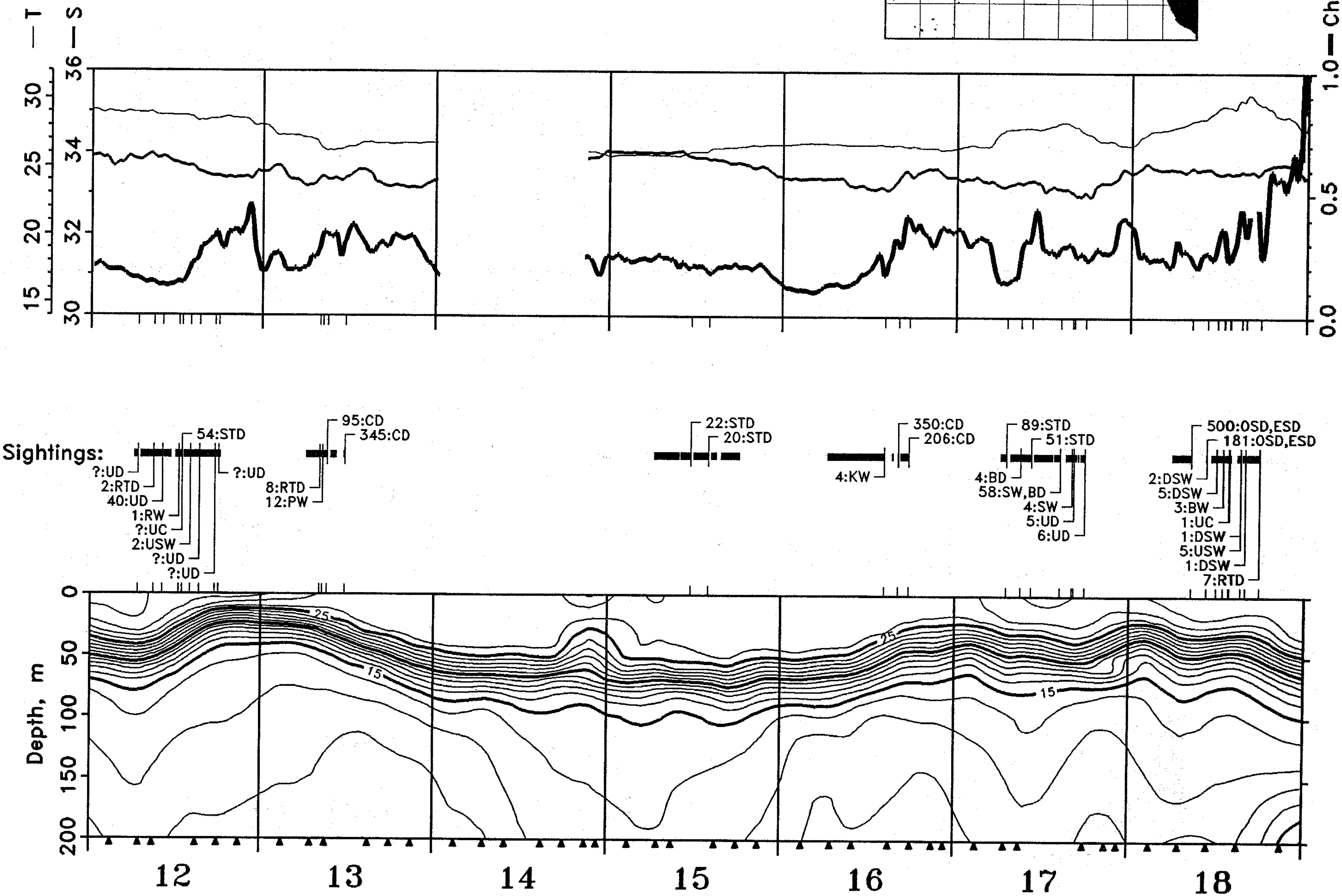


Jordan 1986, Leg 3: 5–11 October

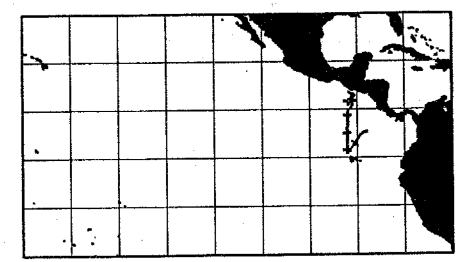


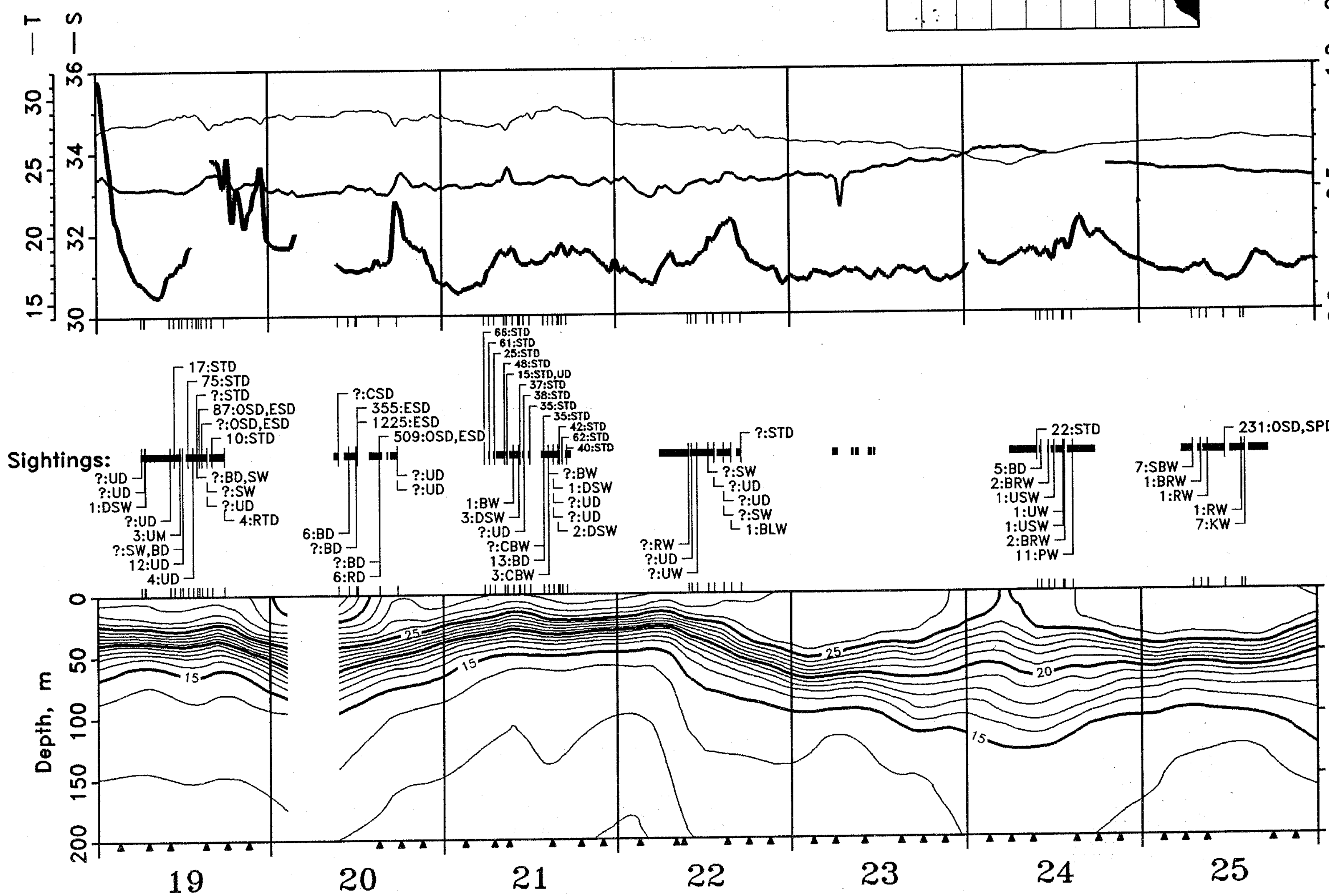
Jordan 1986, Leg 3:
12–18 October



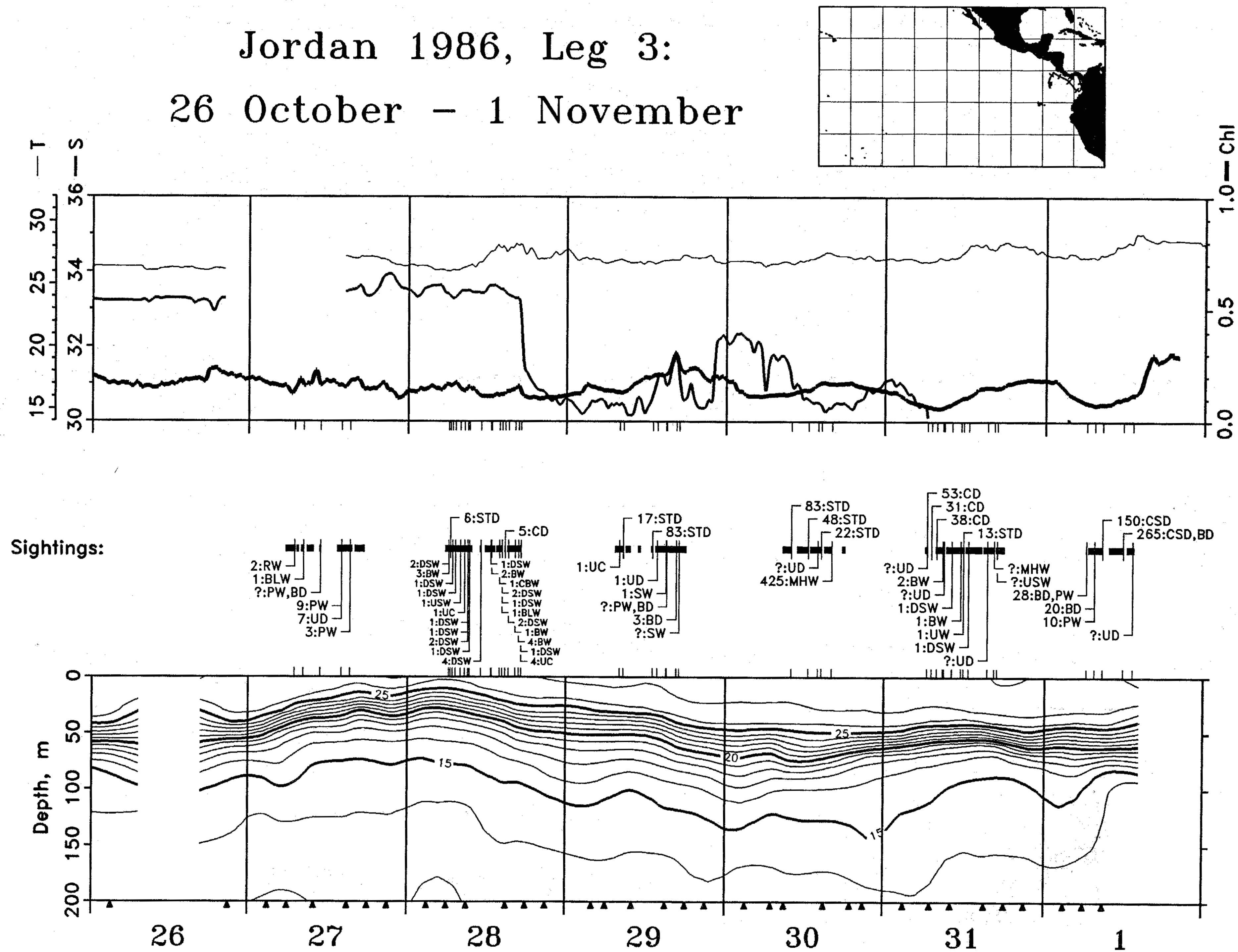


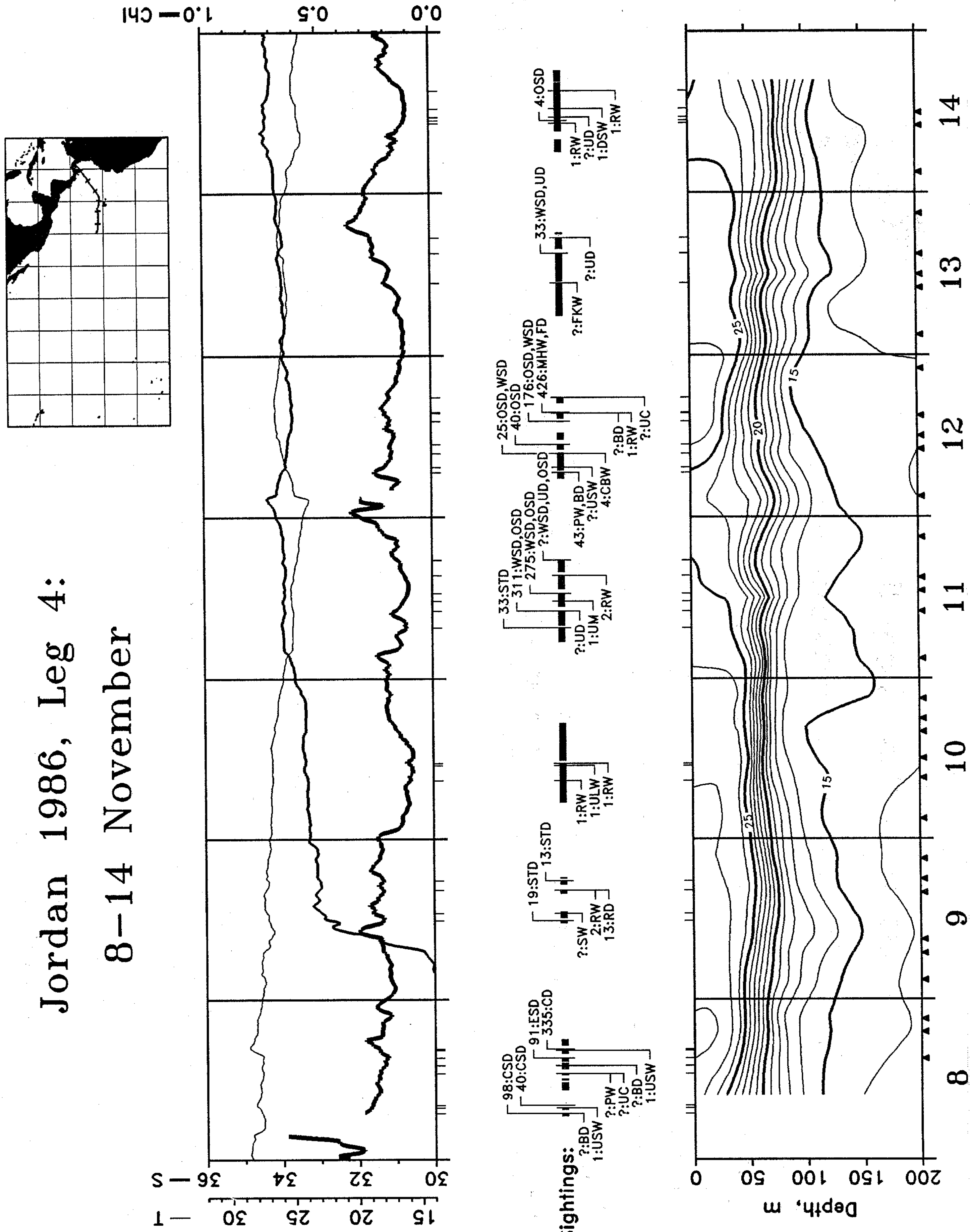
Jordan 1986, Leg 3:
19–25 October





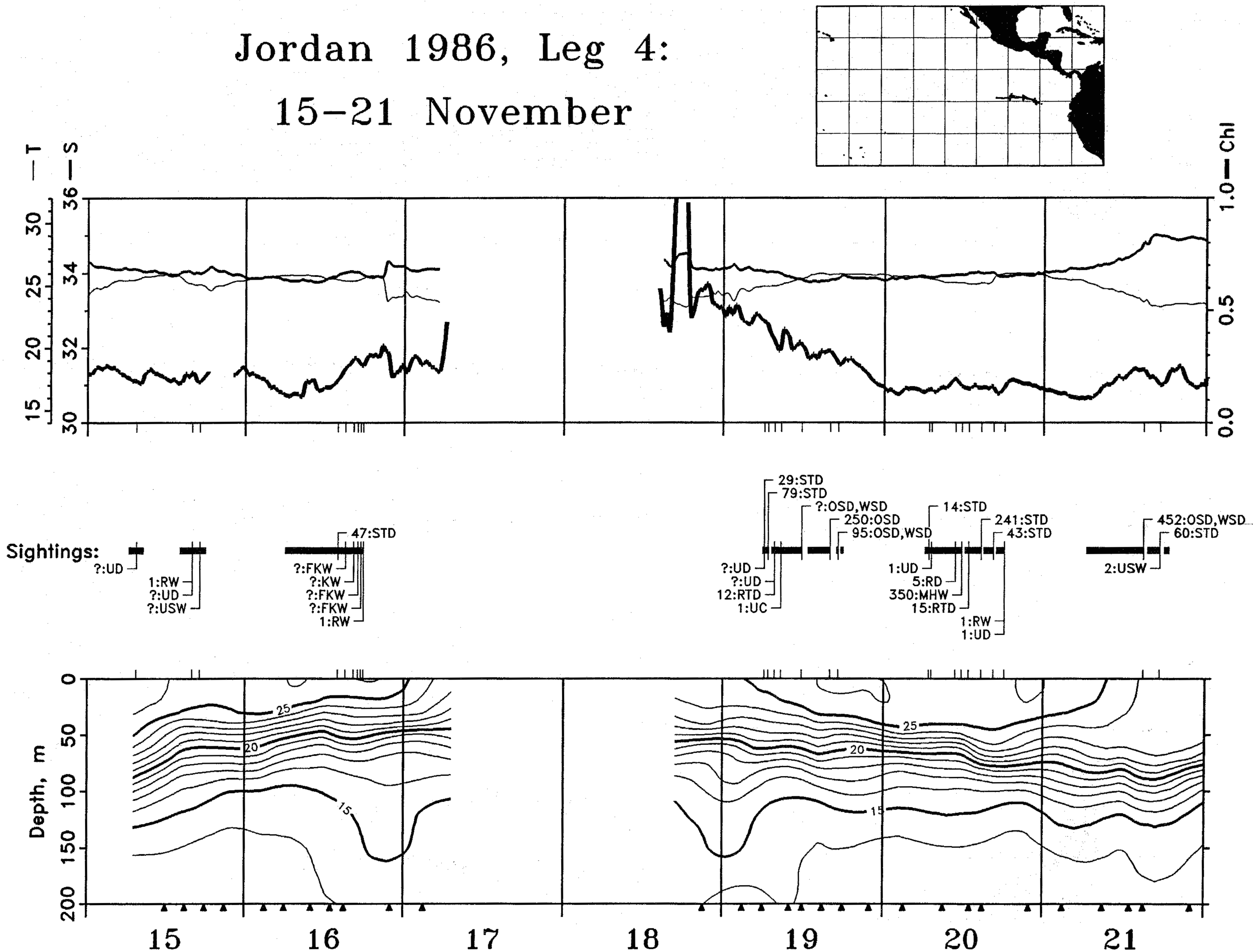
Jordan 1986, Leg 3:
26 October – 1 November





Jordan 1986, Leg 4:
8–14 November
1.0 — Chl
0.5
0.0
36 — S
34
32
30
— T
30
25
20
15
Sightings:
?:BD
1:USW
98:CSD
40:CSD
?:PW
?:UC
?:BD
1:USW
91:ESD
335:CD
?:SW
2:RW
13:RD
19:STD
13:STD
1:RW
1:ULW
1:RW
?:UD
1:UM
2:RW
33:STD
311:WSD,OSD
275:WSD,OSD
?:WSD,UD,OSD
43:PW,BD
?:USW
4:CBW
25:OSD,WSD
40:OSD
176:OSD,WSD
426:MHW,FD
?:BD
1:RW
?:UC
?:FKW
?:UD
33:WSD,UD
1:RW
?:UD
1:DSW
1:RW
4:OSD
25
20
15
0
50
100
150
200
Depth, m
8
9
10
11
12
13
14

Jordan 1986, Leg 4:
15–21 November



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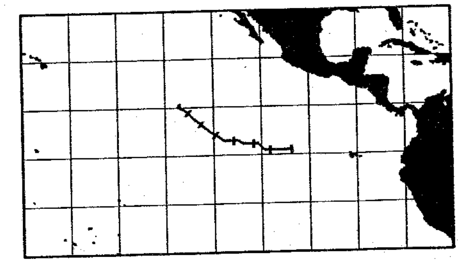
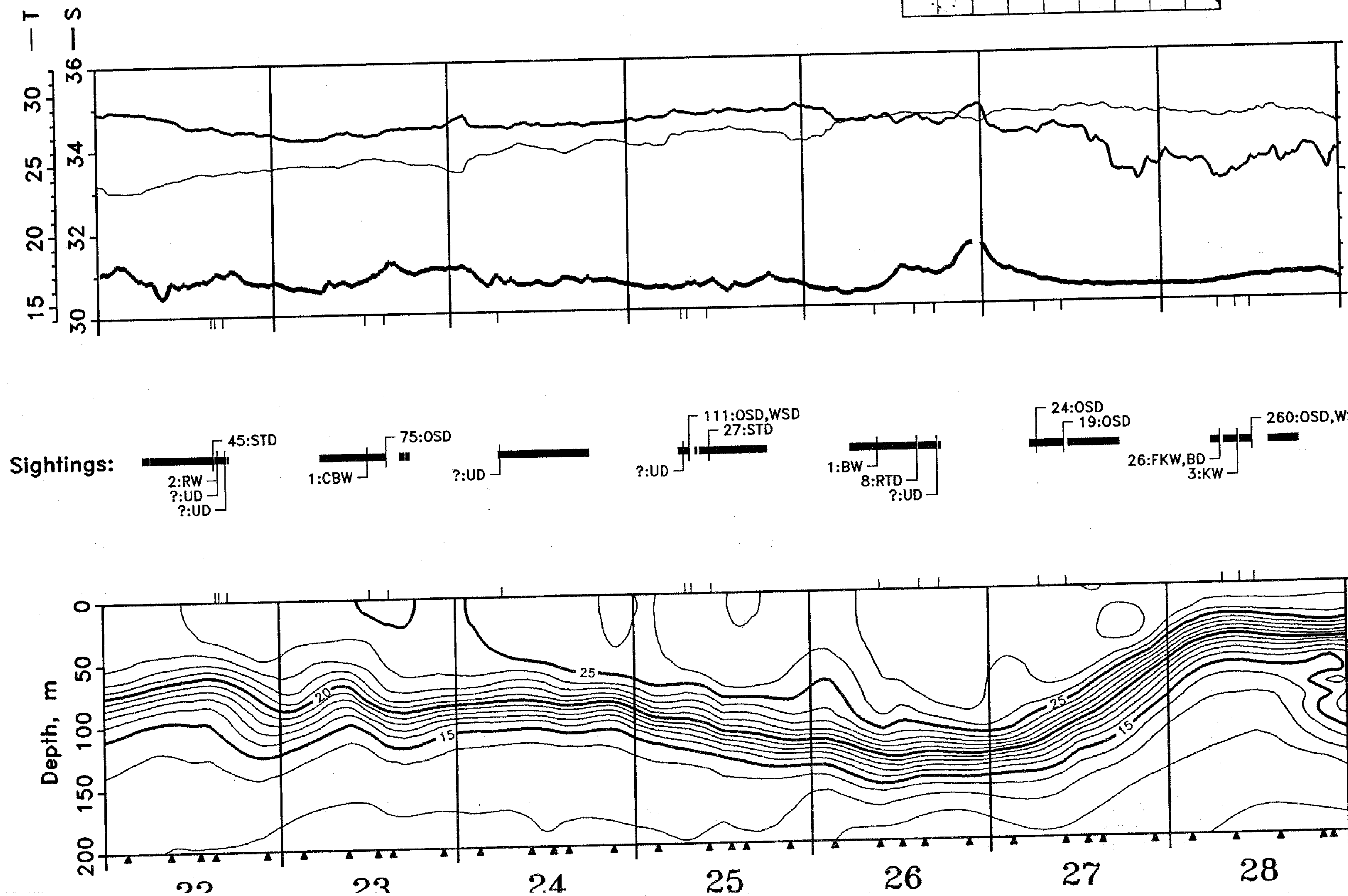
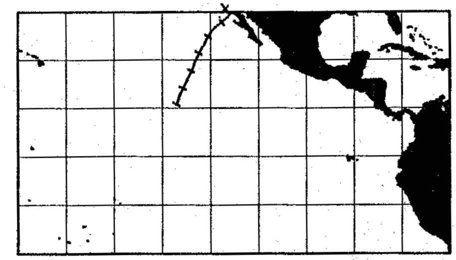
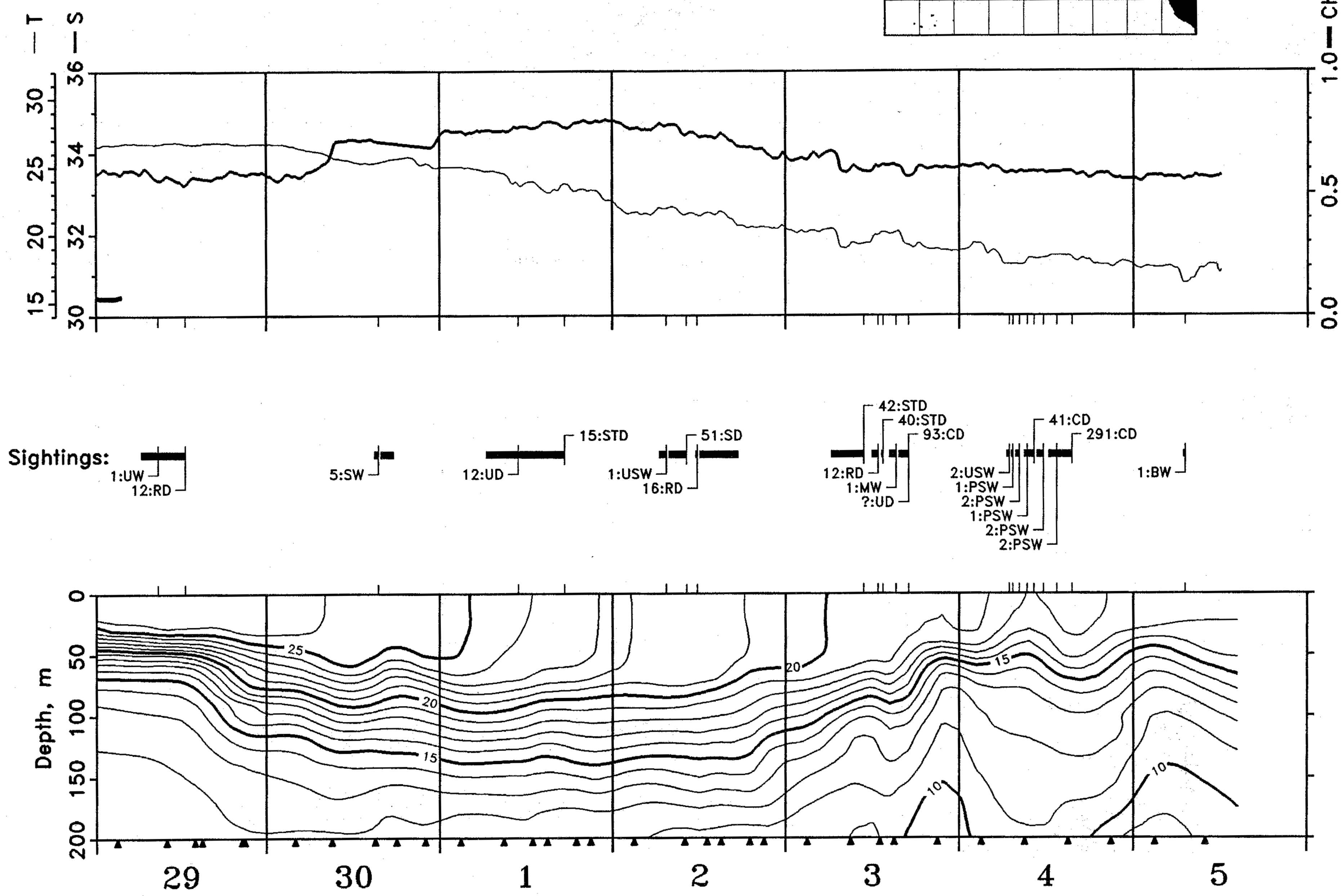
22–28 November





Jordan 1986, Leg 4:
29 November – 5 December





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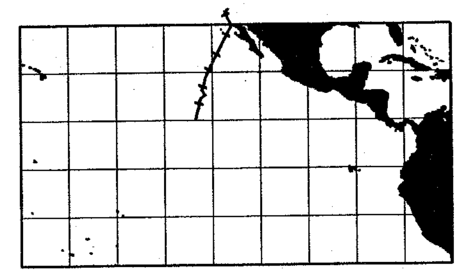
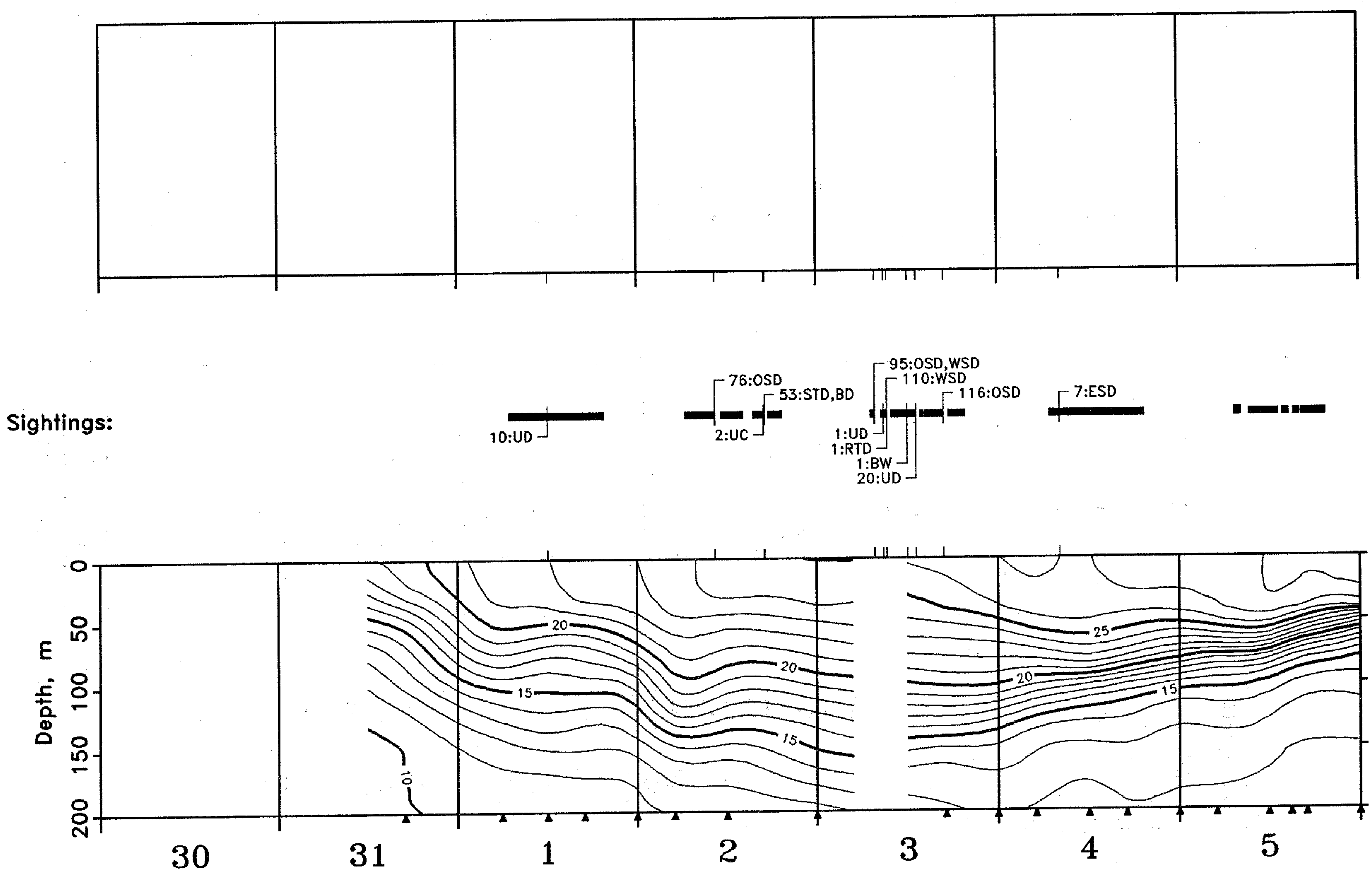
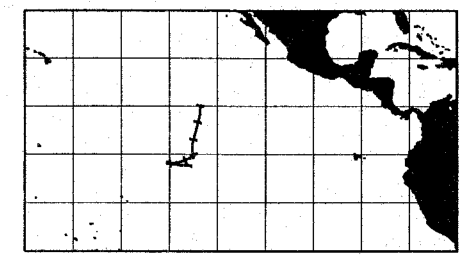
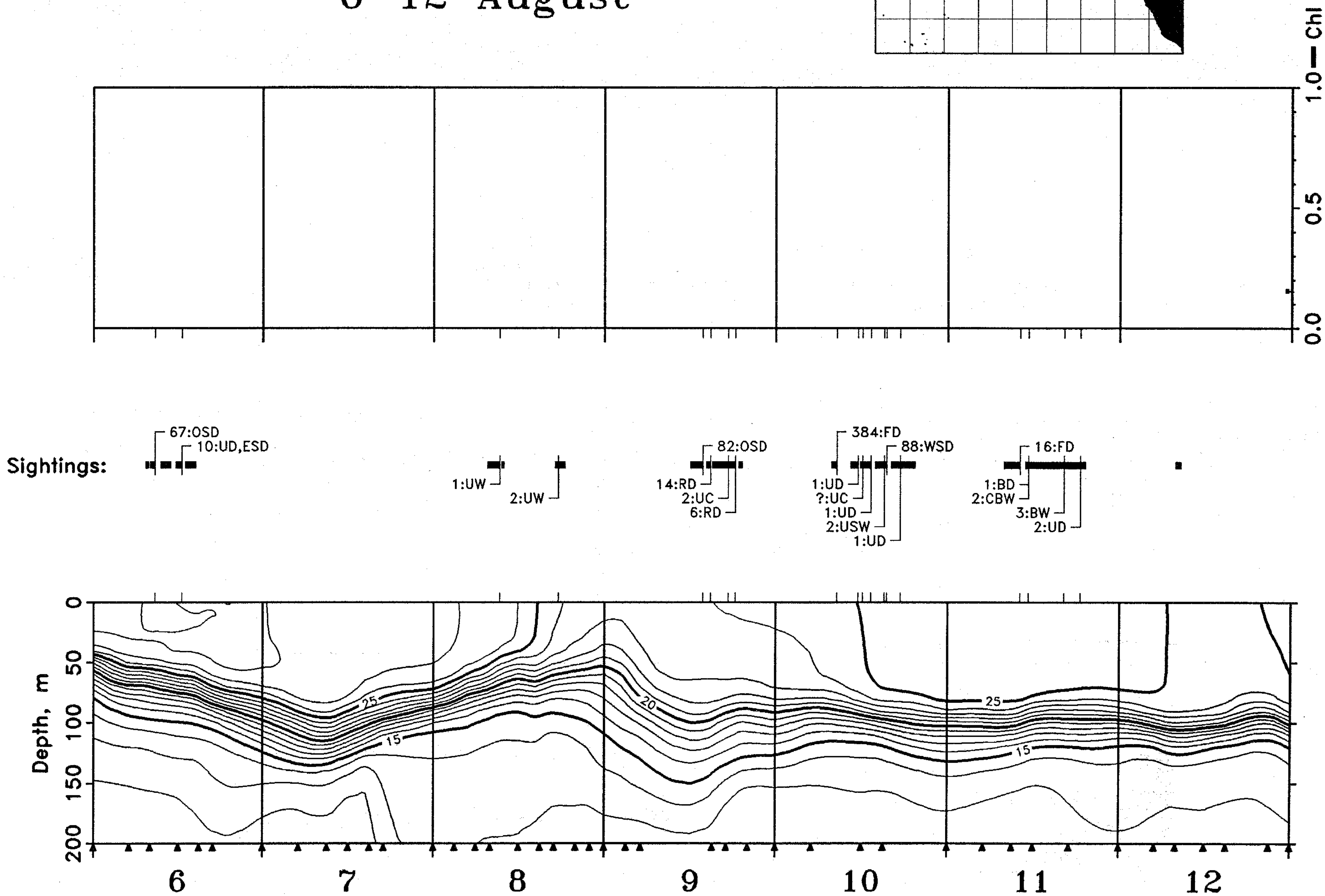
30 July – 5 August





McArthur 1986, Leg 1:
6–12 August





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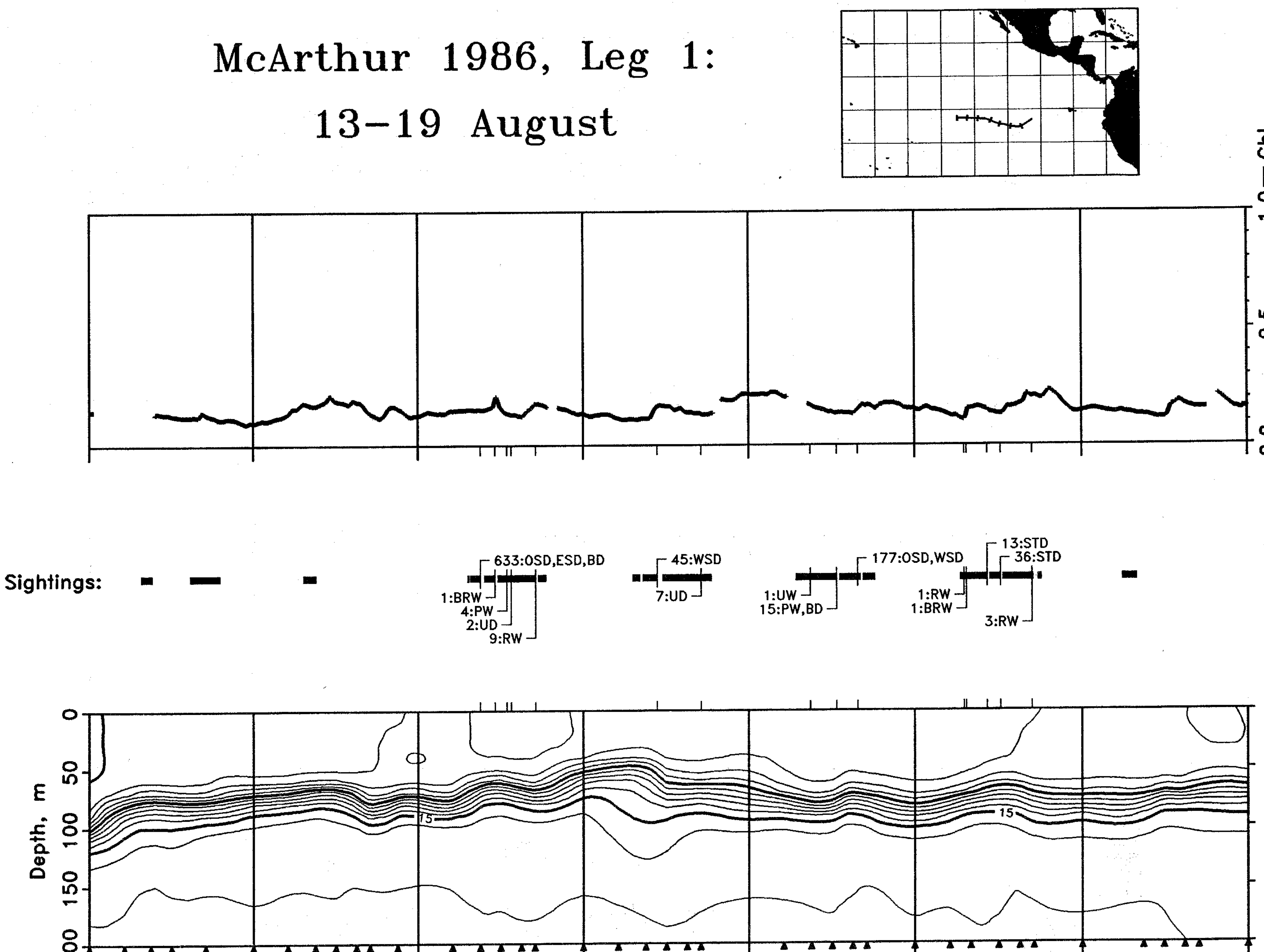
13–19 August



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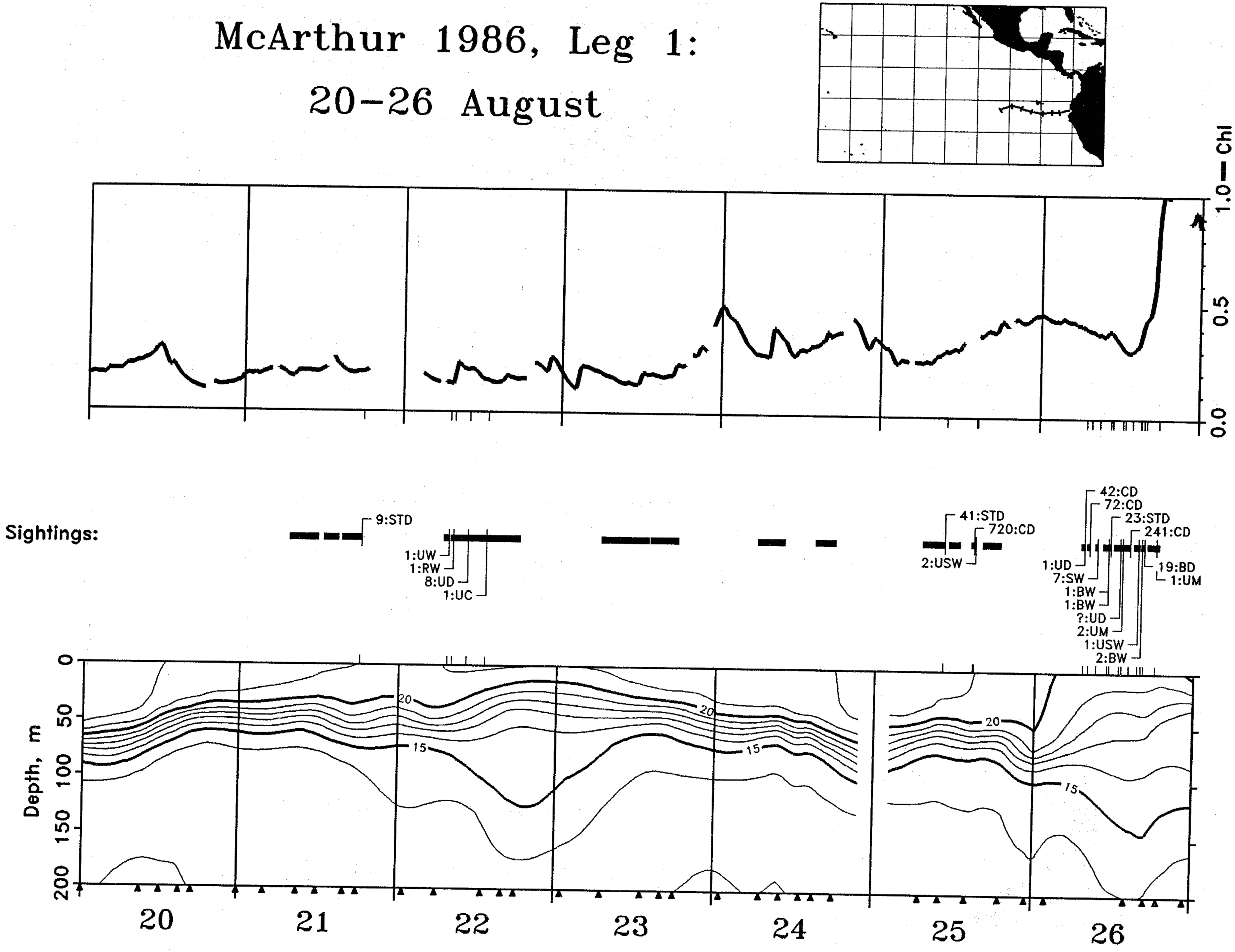

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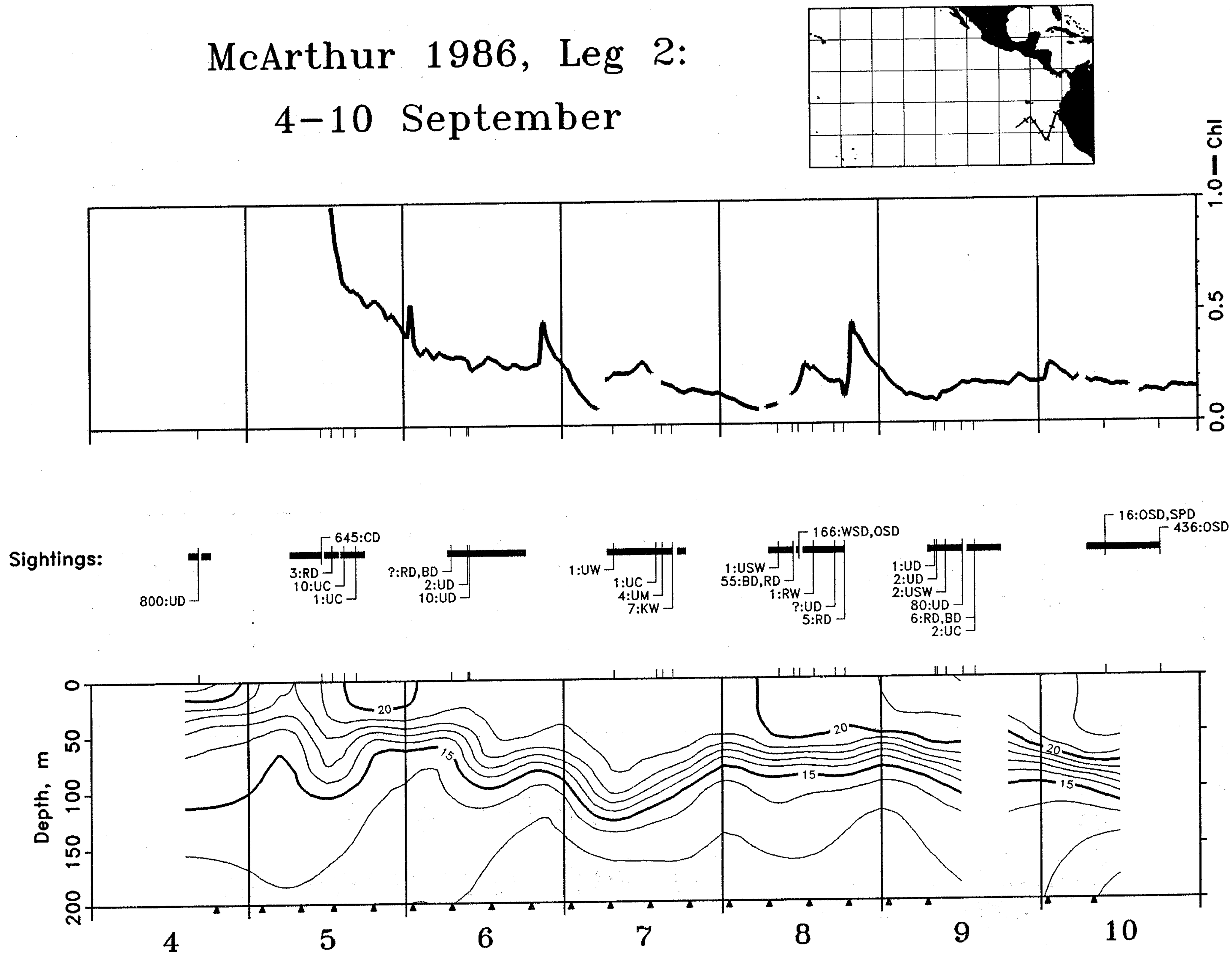
4–10 September



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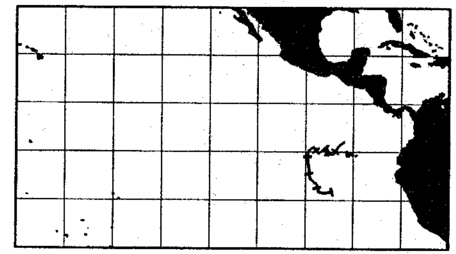
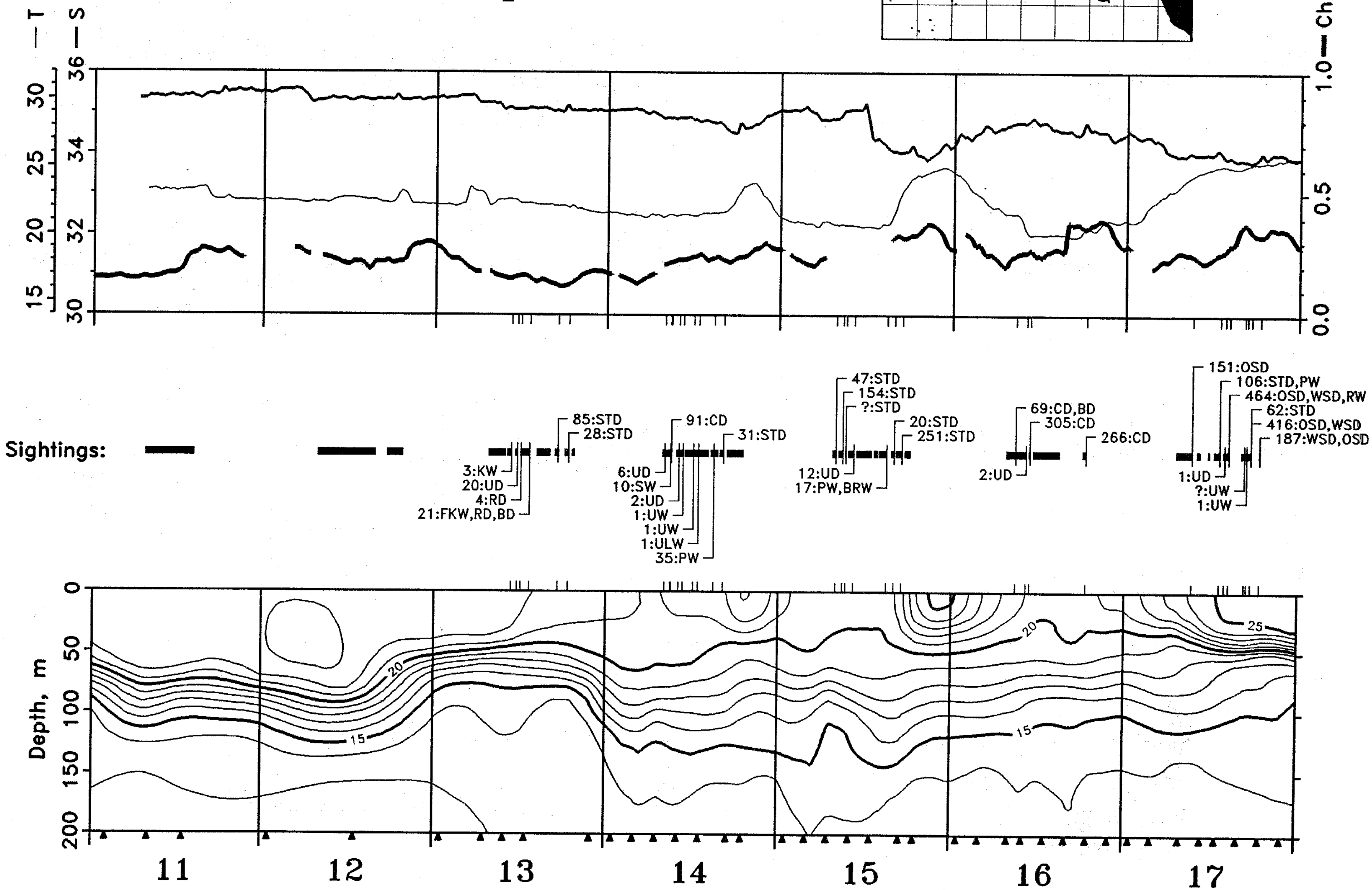
11–17 September





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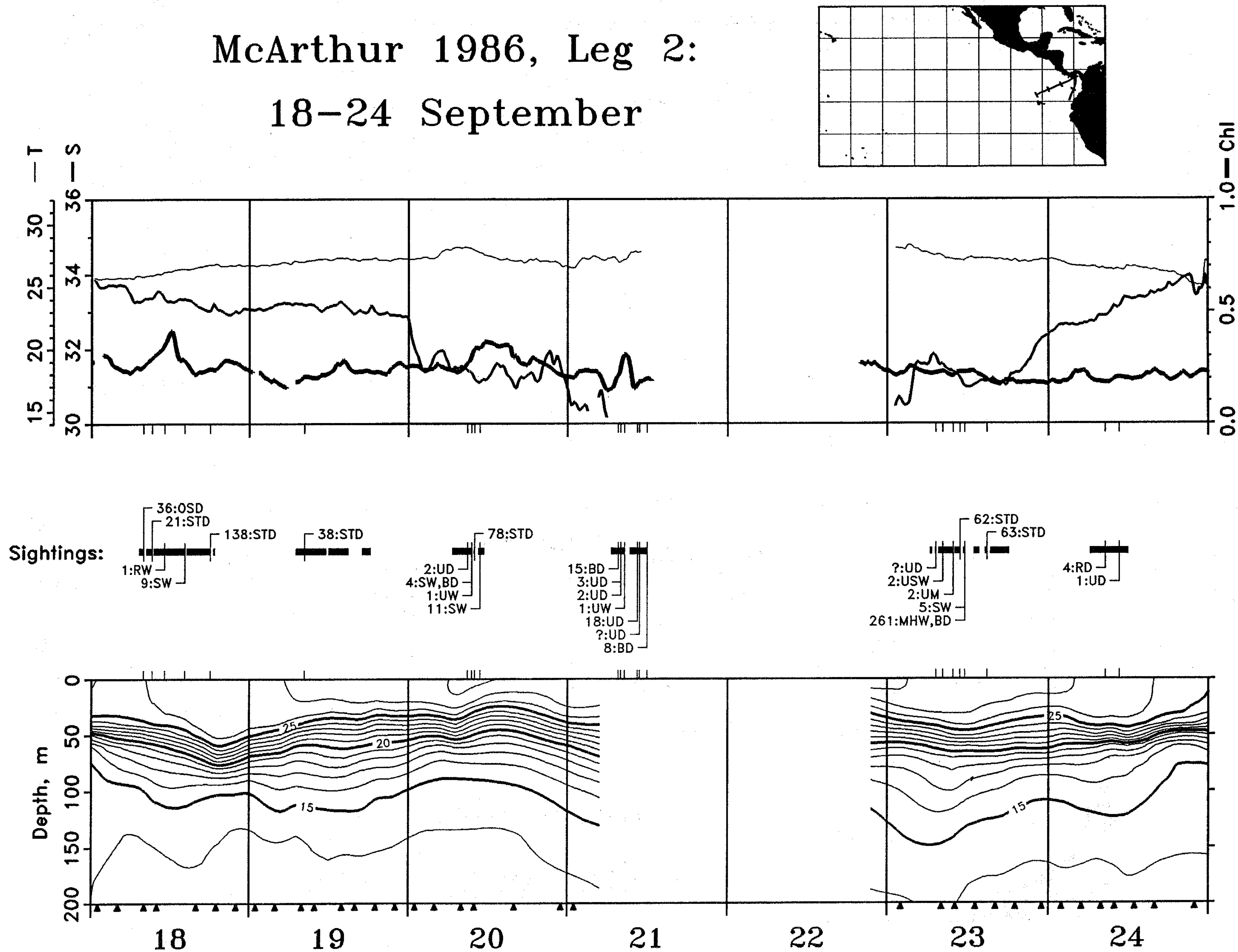

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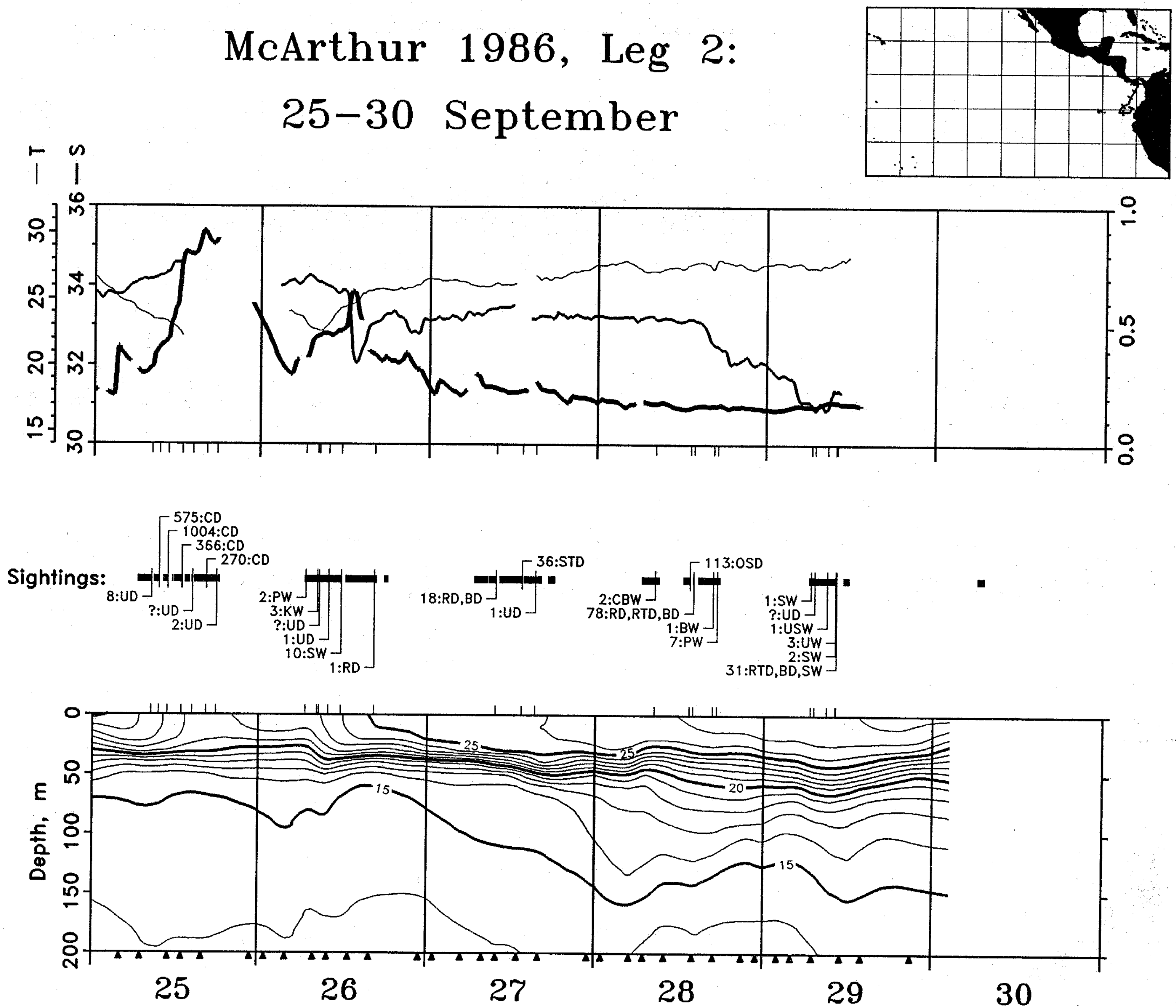
25–30 September



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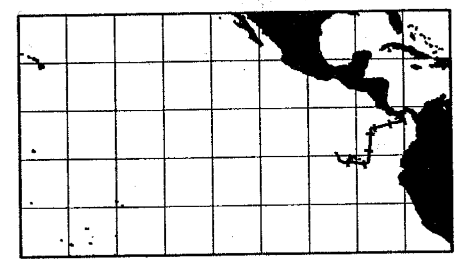
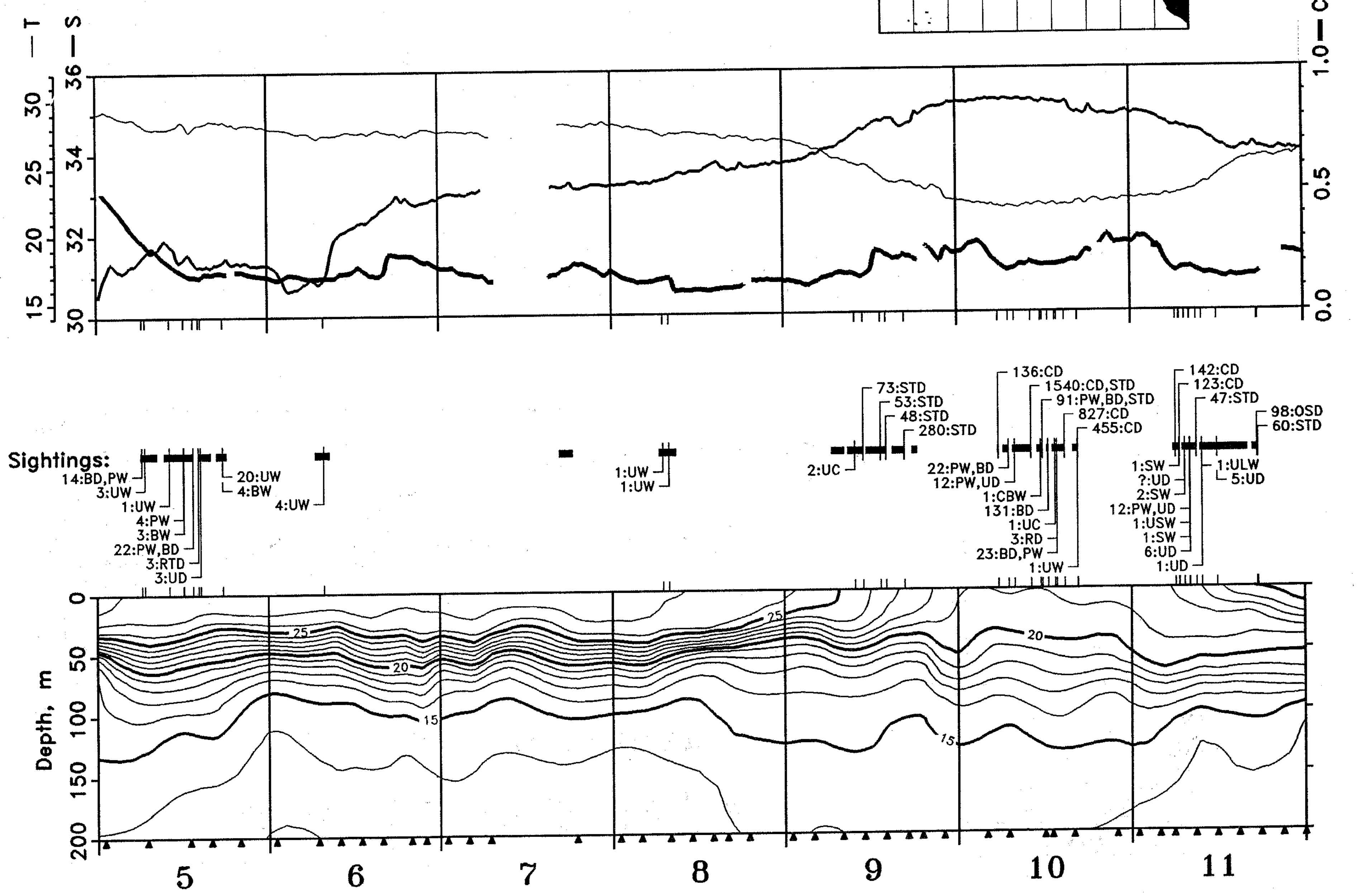
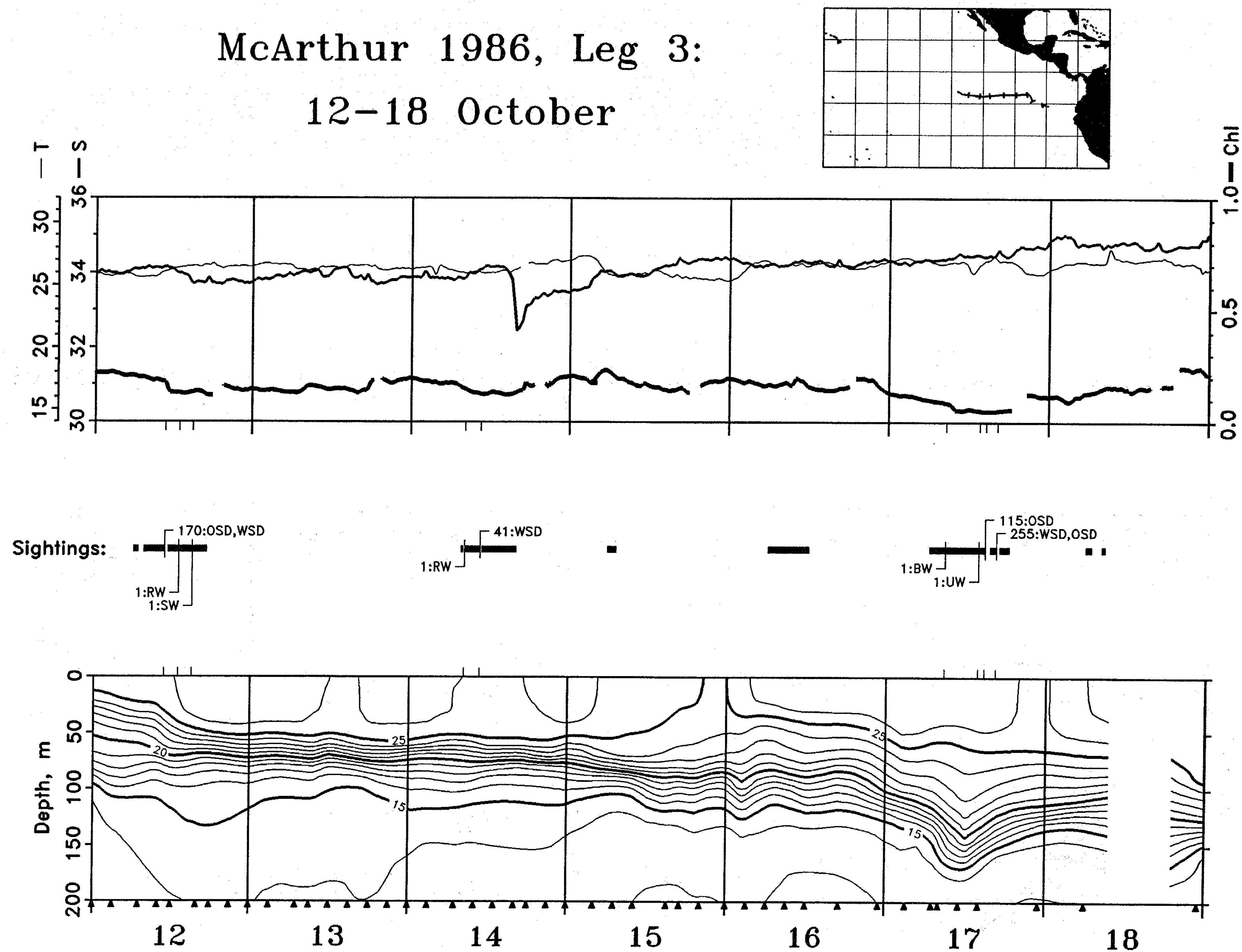
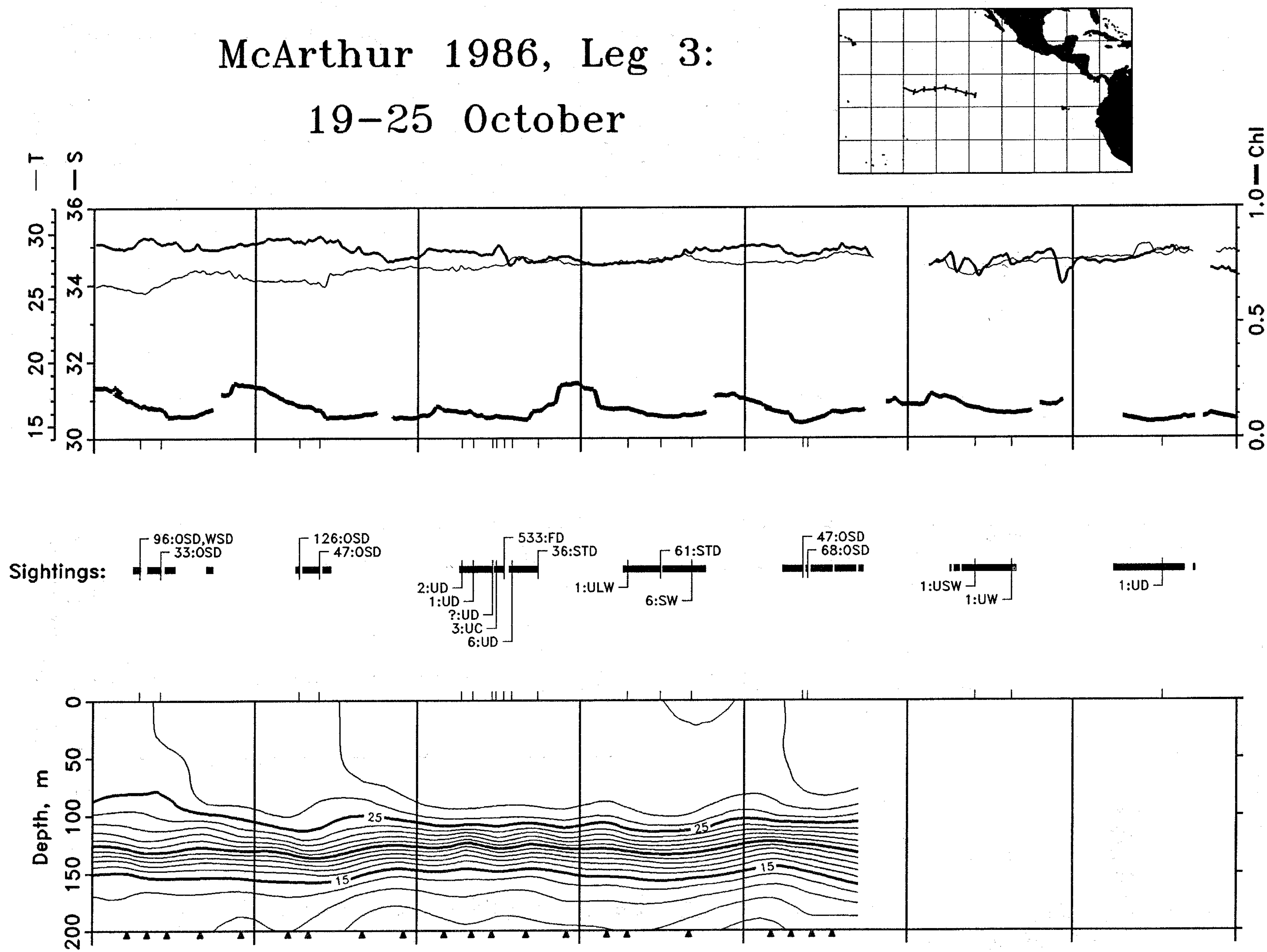




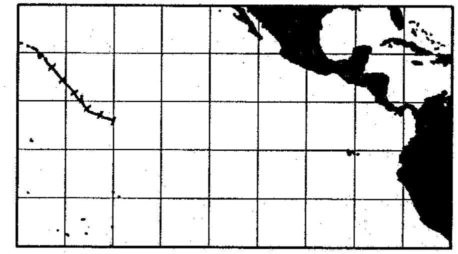
McArthur 1986, Leg 3:
12–18 October

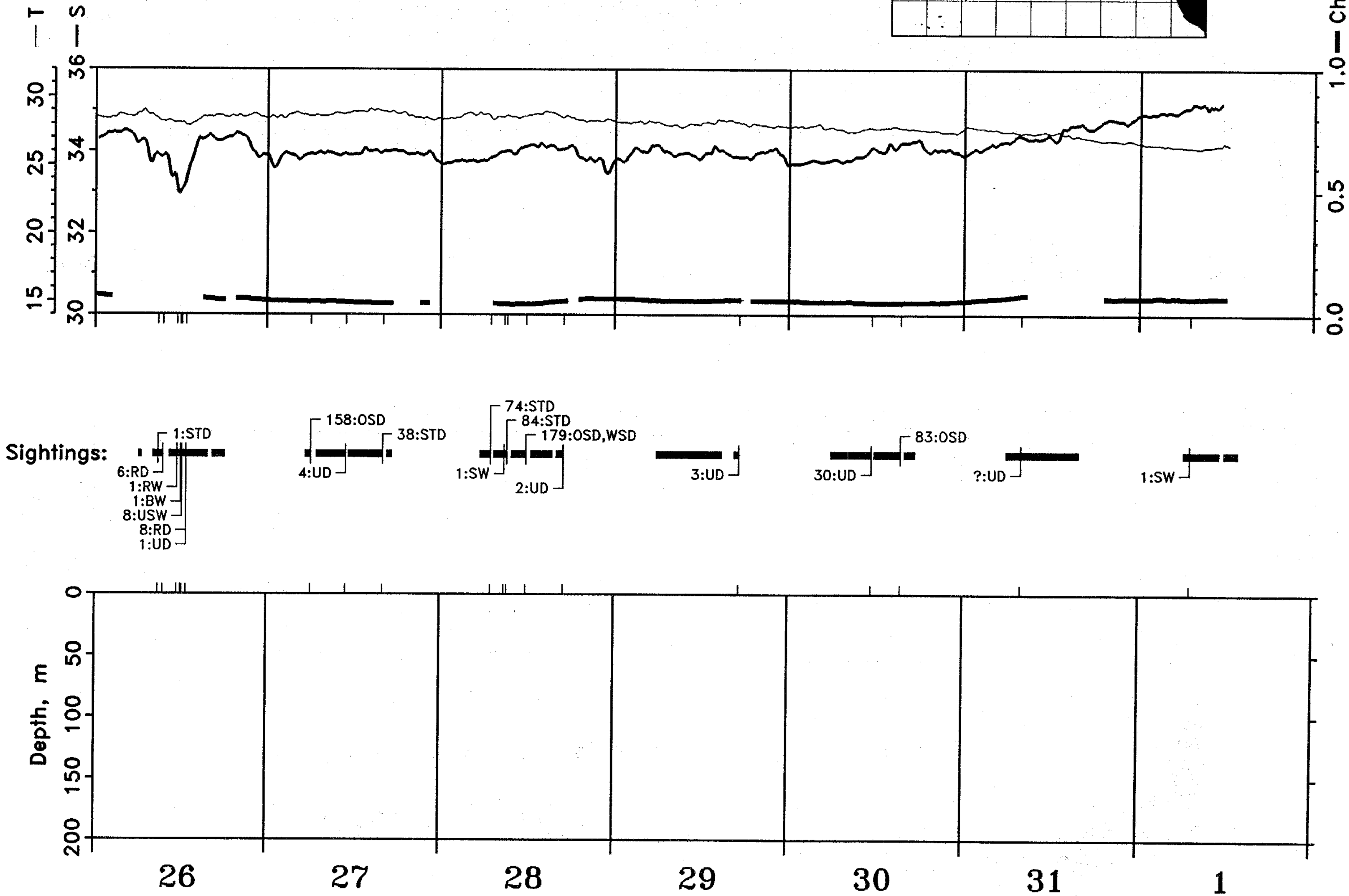


McArthur 1986, Leg 3:
19–25 October

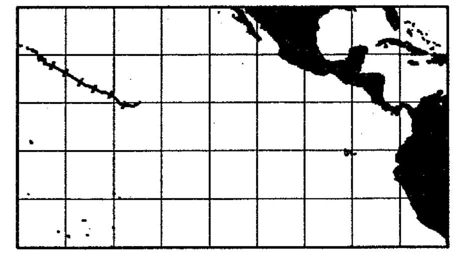


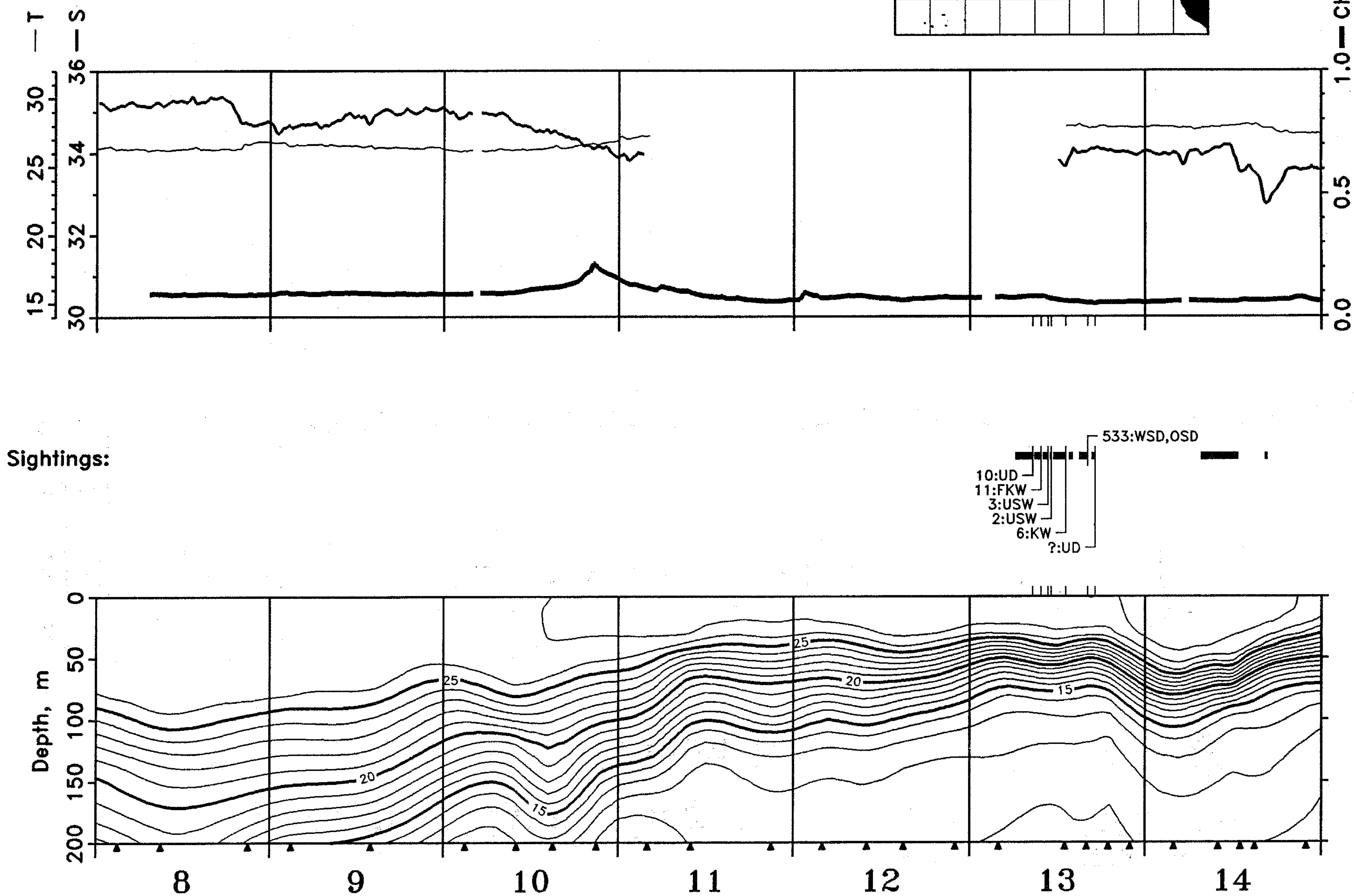
McArthur 1986, Leg 3:
26 October – 1 November



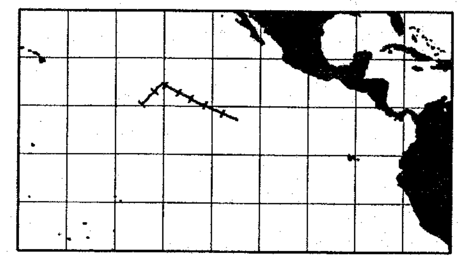


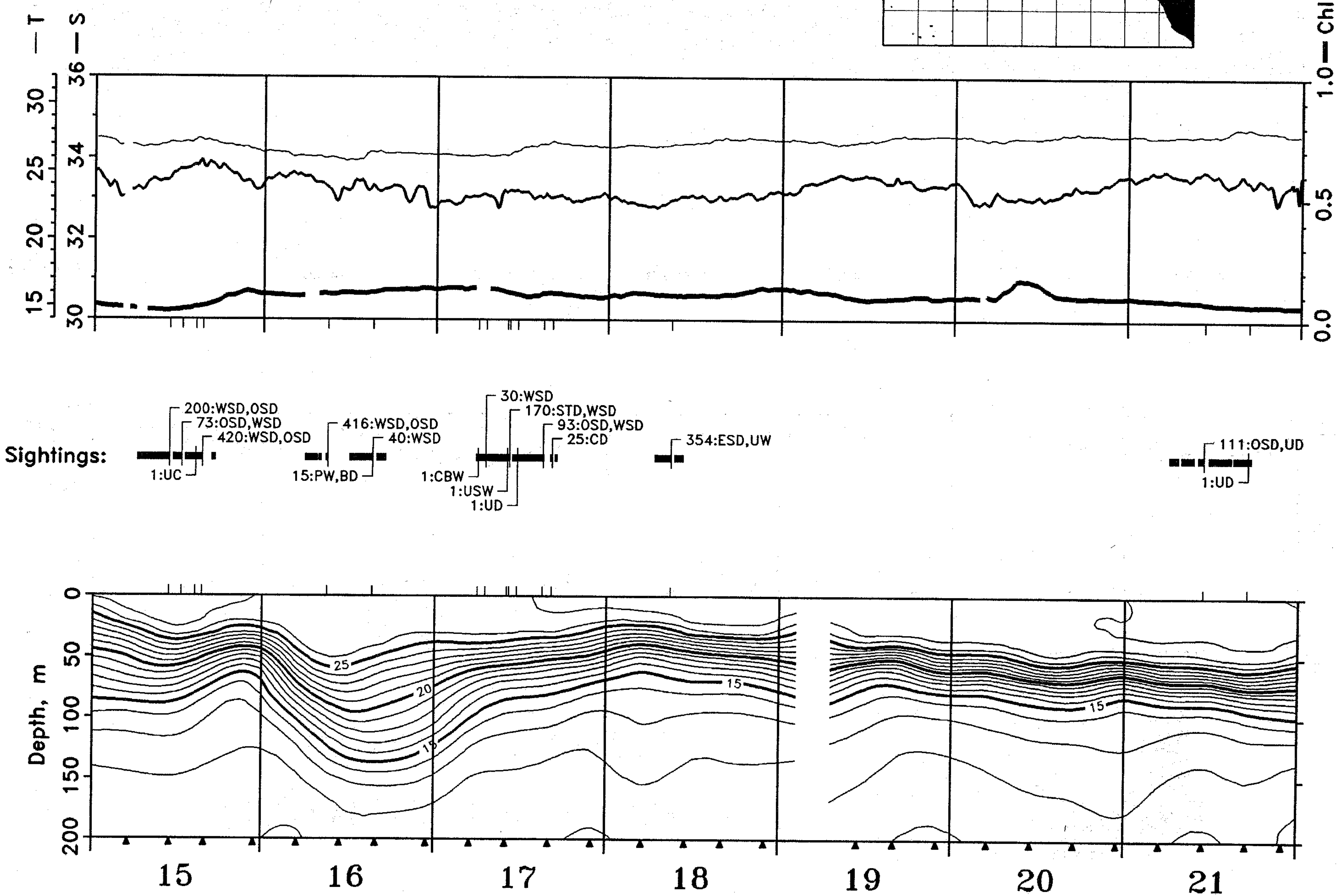
McArthur 1986, Leg 4:
8–14 November



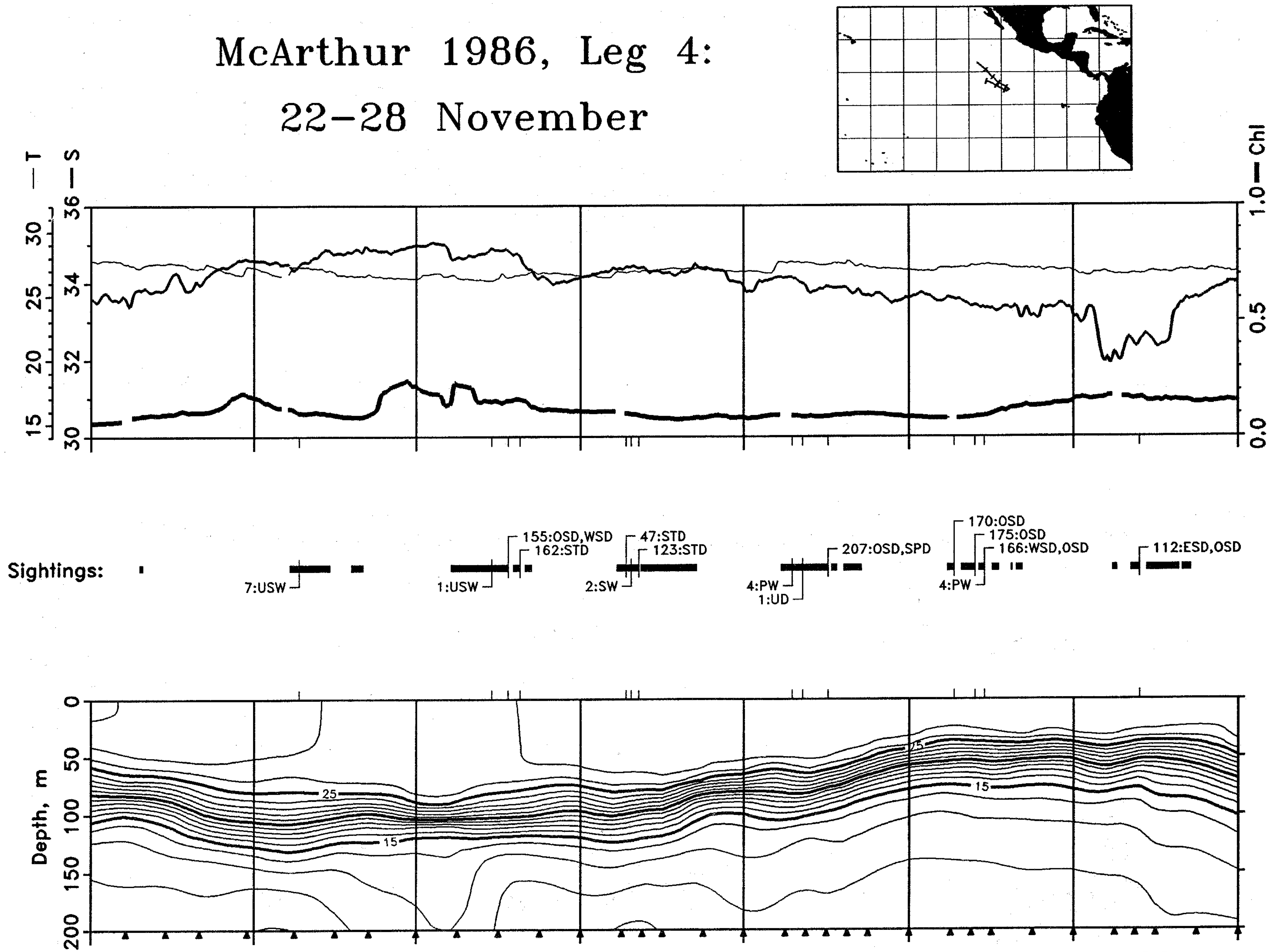


McArthur 1986, Leg 4:
15–21 November

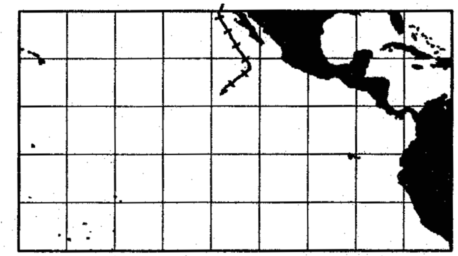


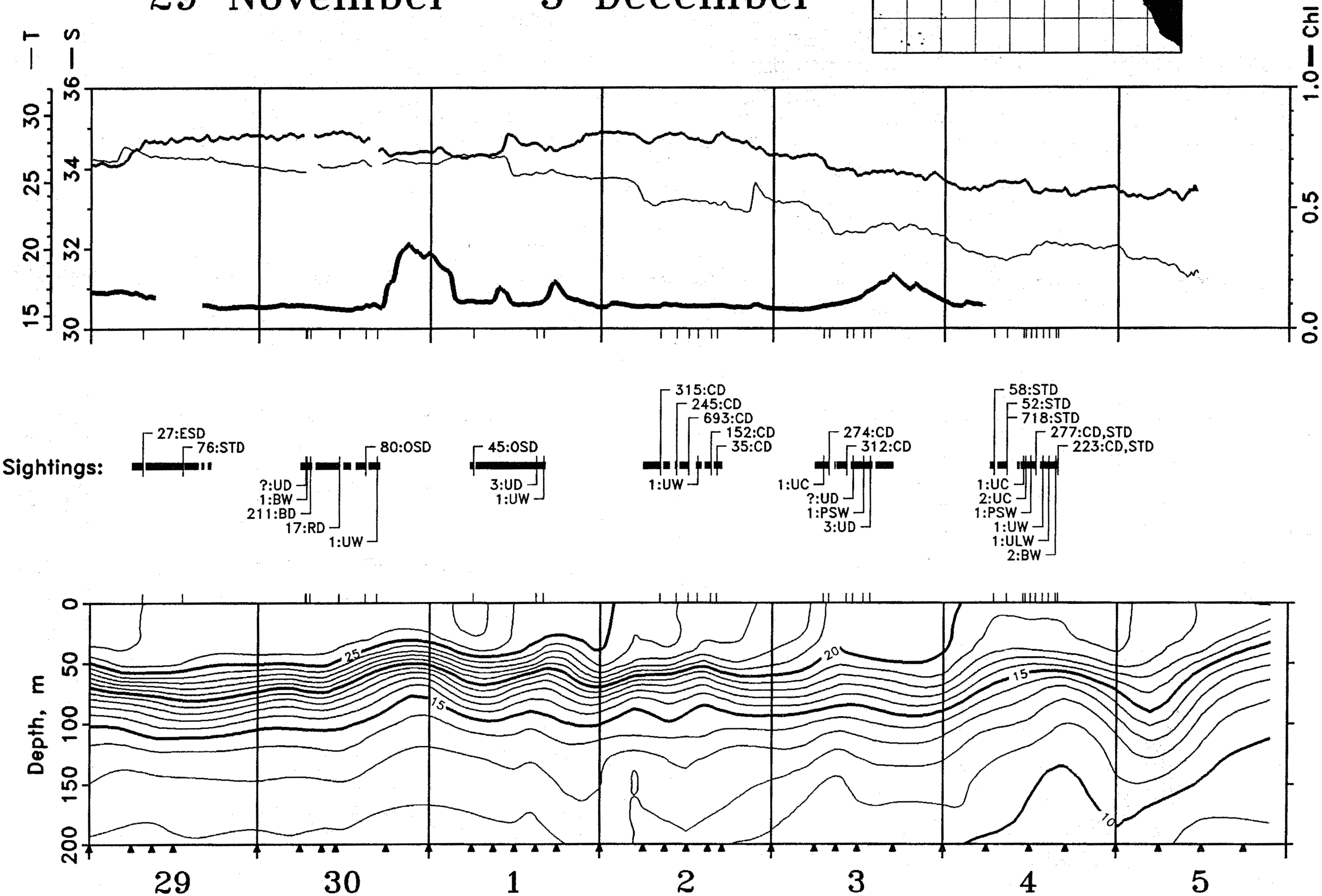


McArthur 1986, Leg 4:
22–28 November

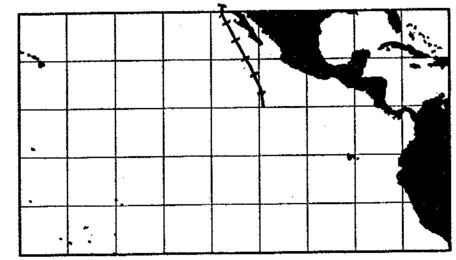


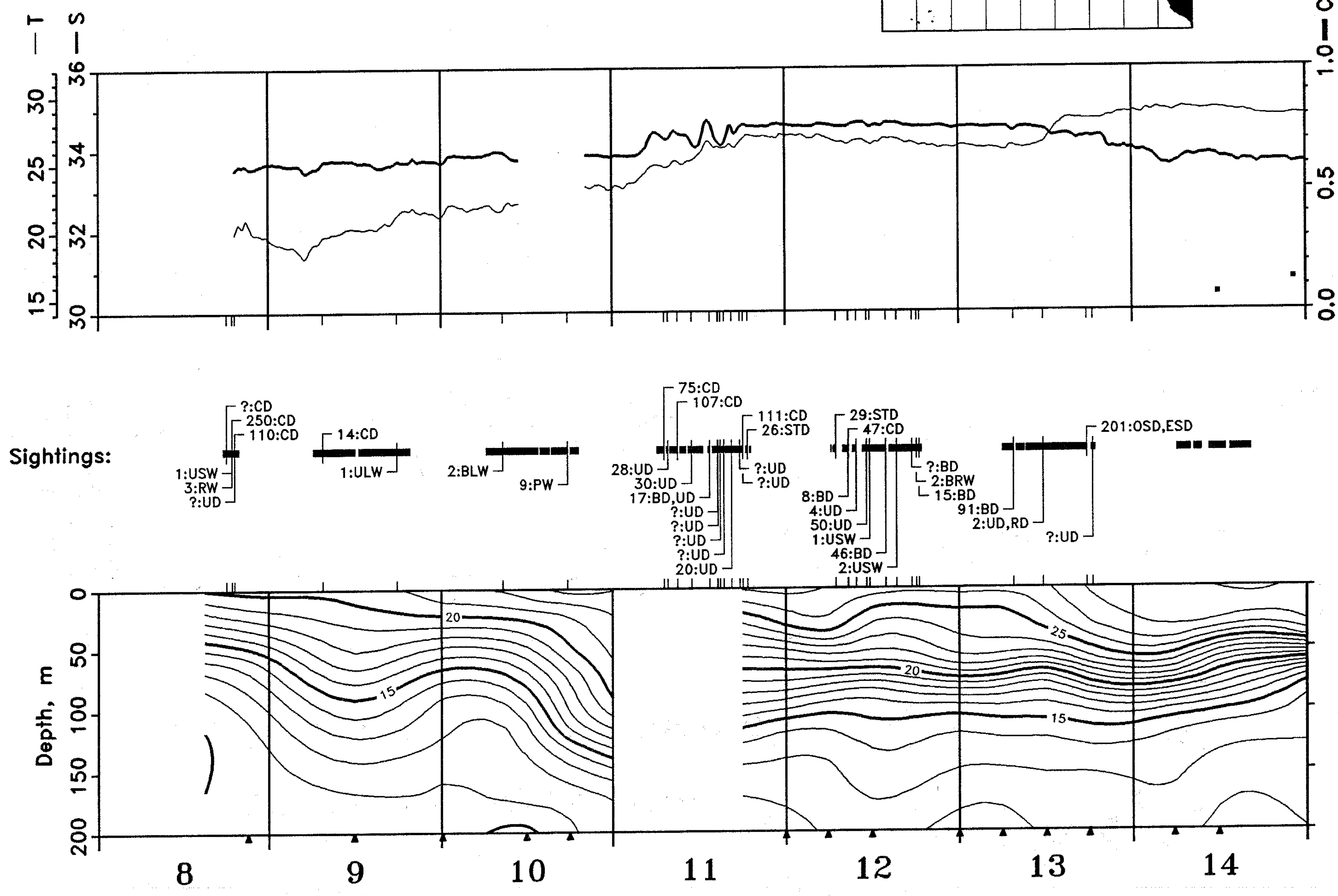
McArthur 1986, Leg 4:
29 November – 5 December



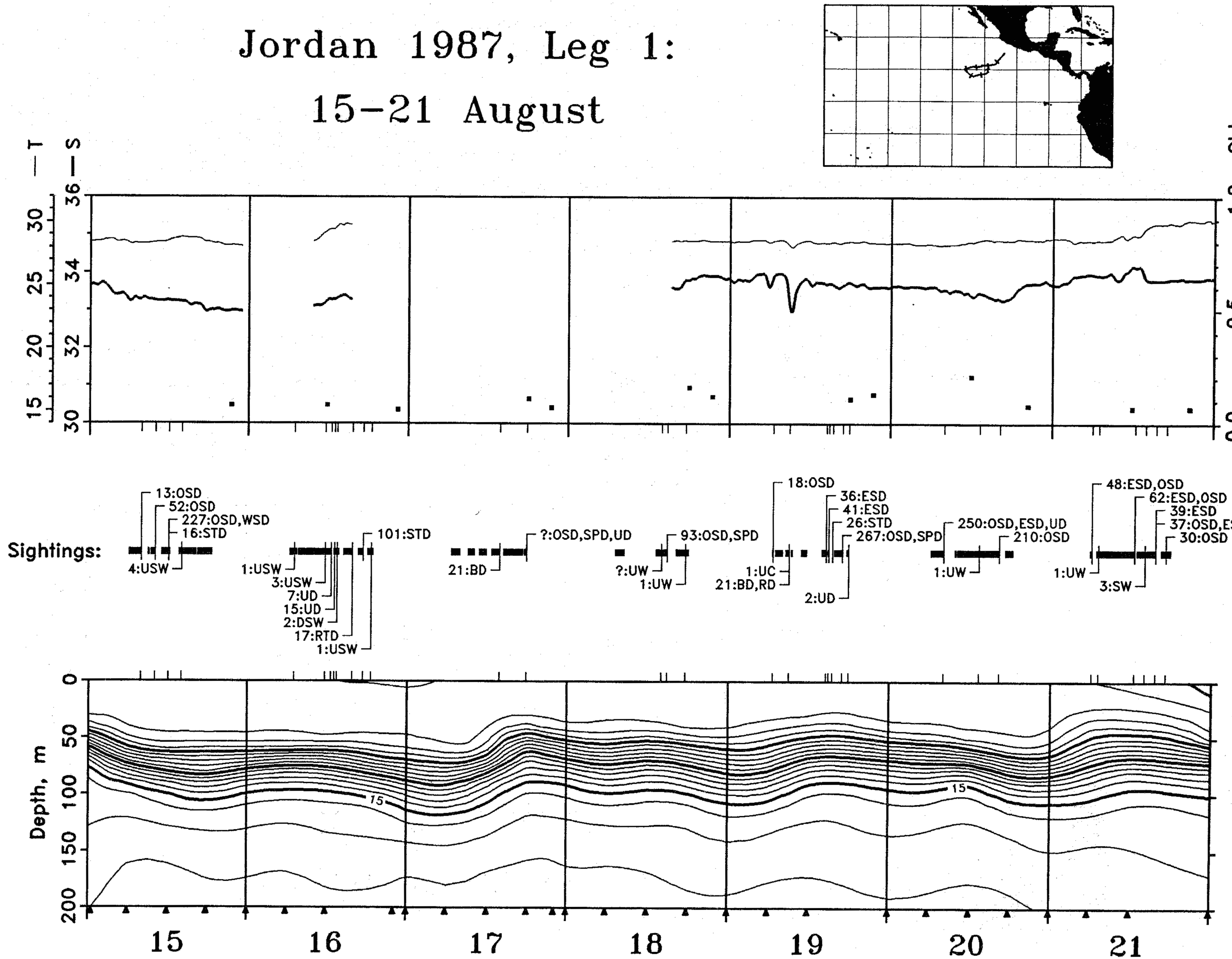


Jordan 1987, Leg 1:
8–14 August

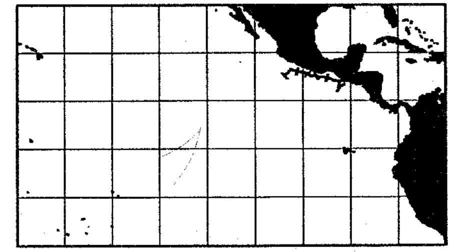


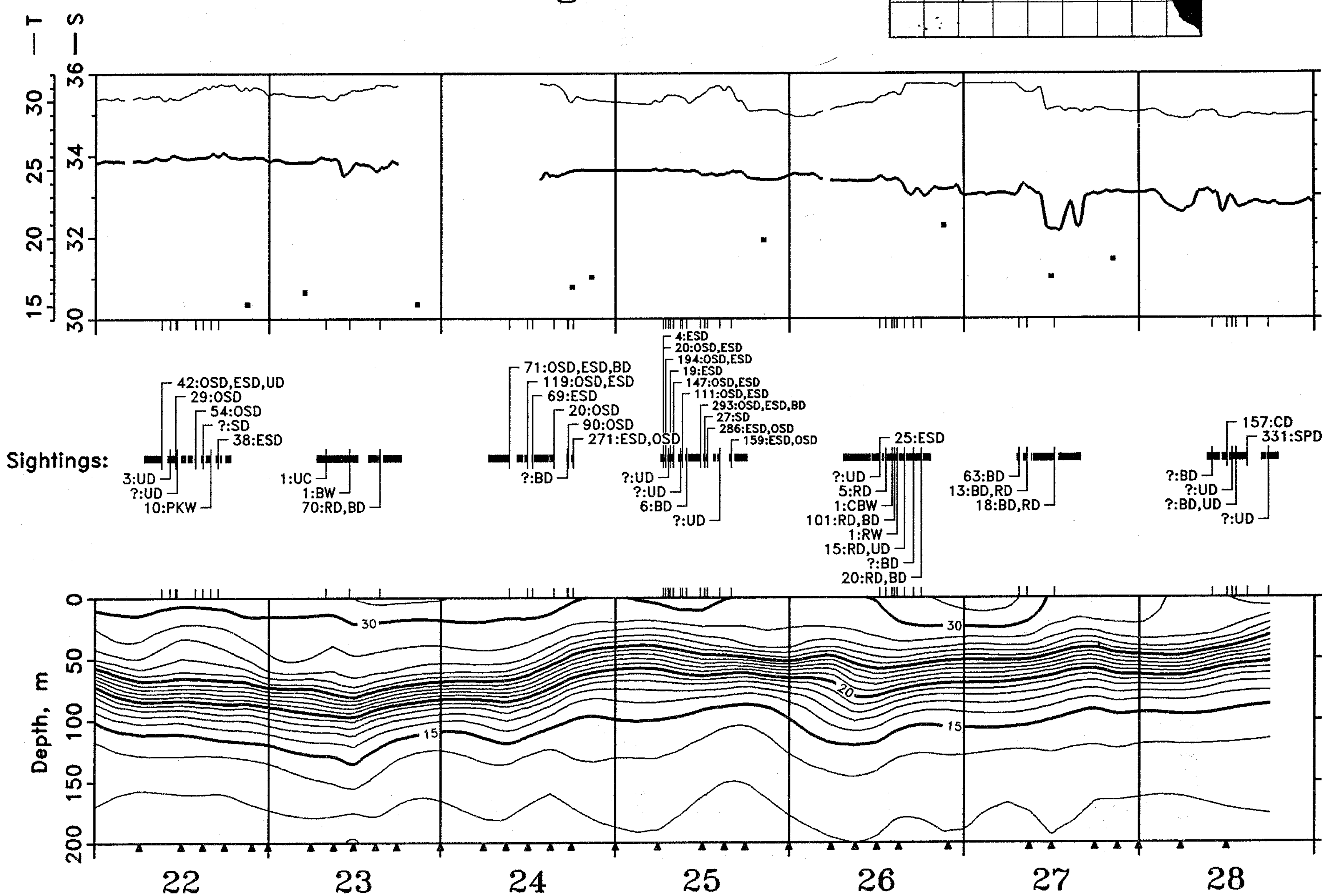


Jordan 1987, Leg 1:
15–21 August

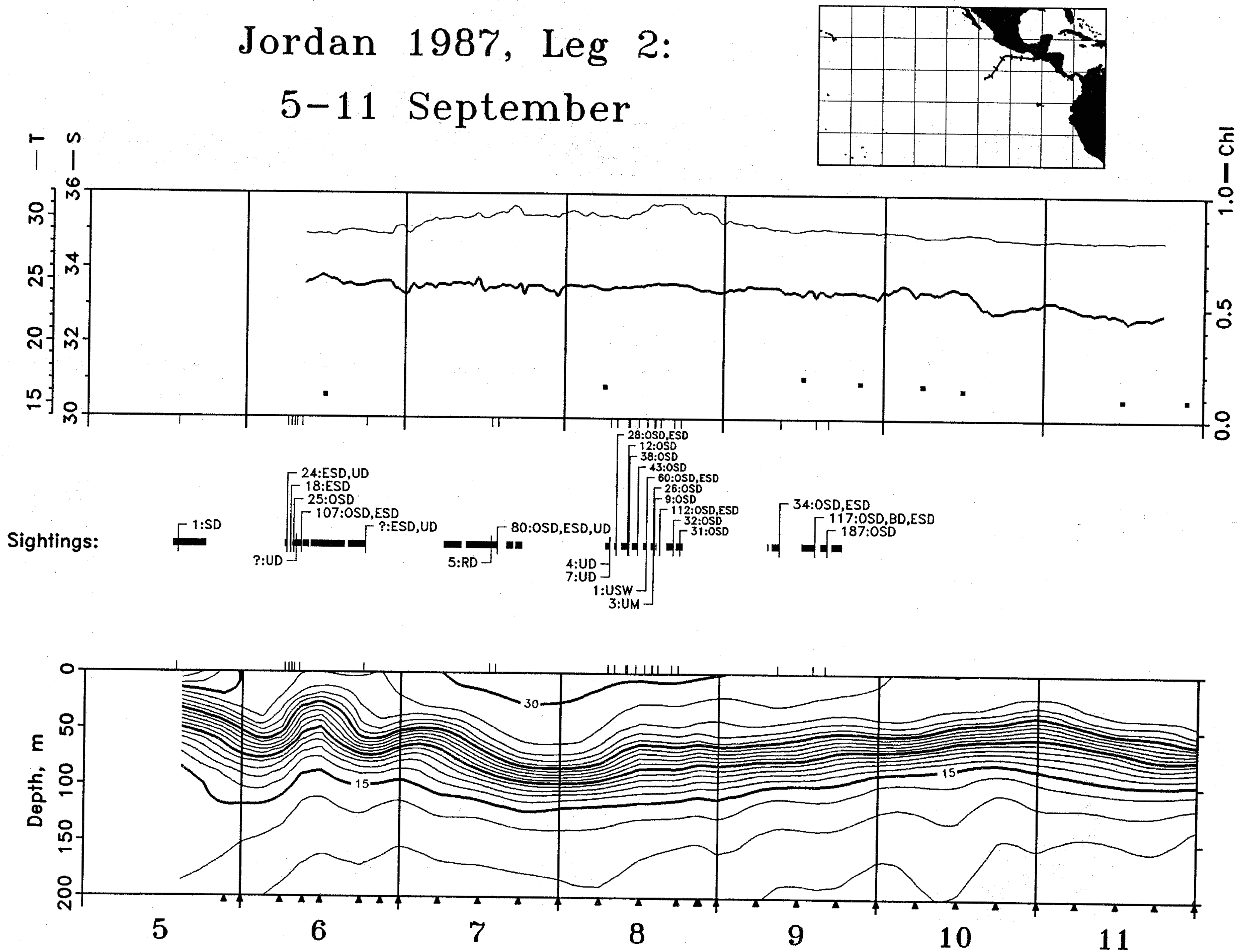


Jordan 1987, Leg 1:
22–28 August

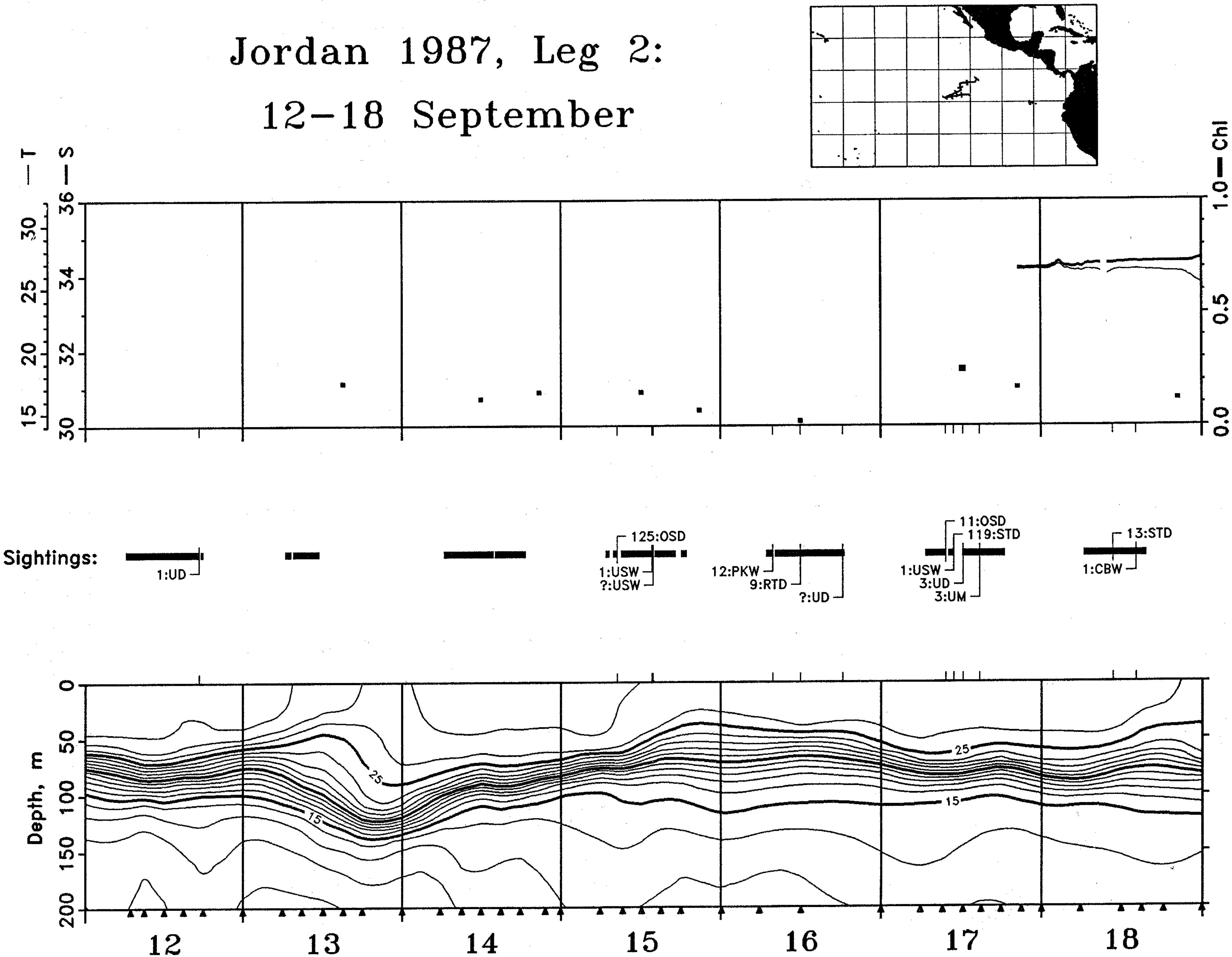




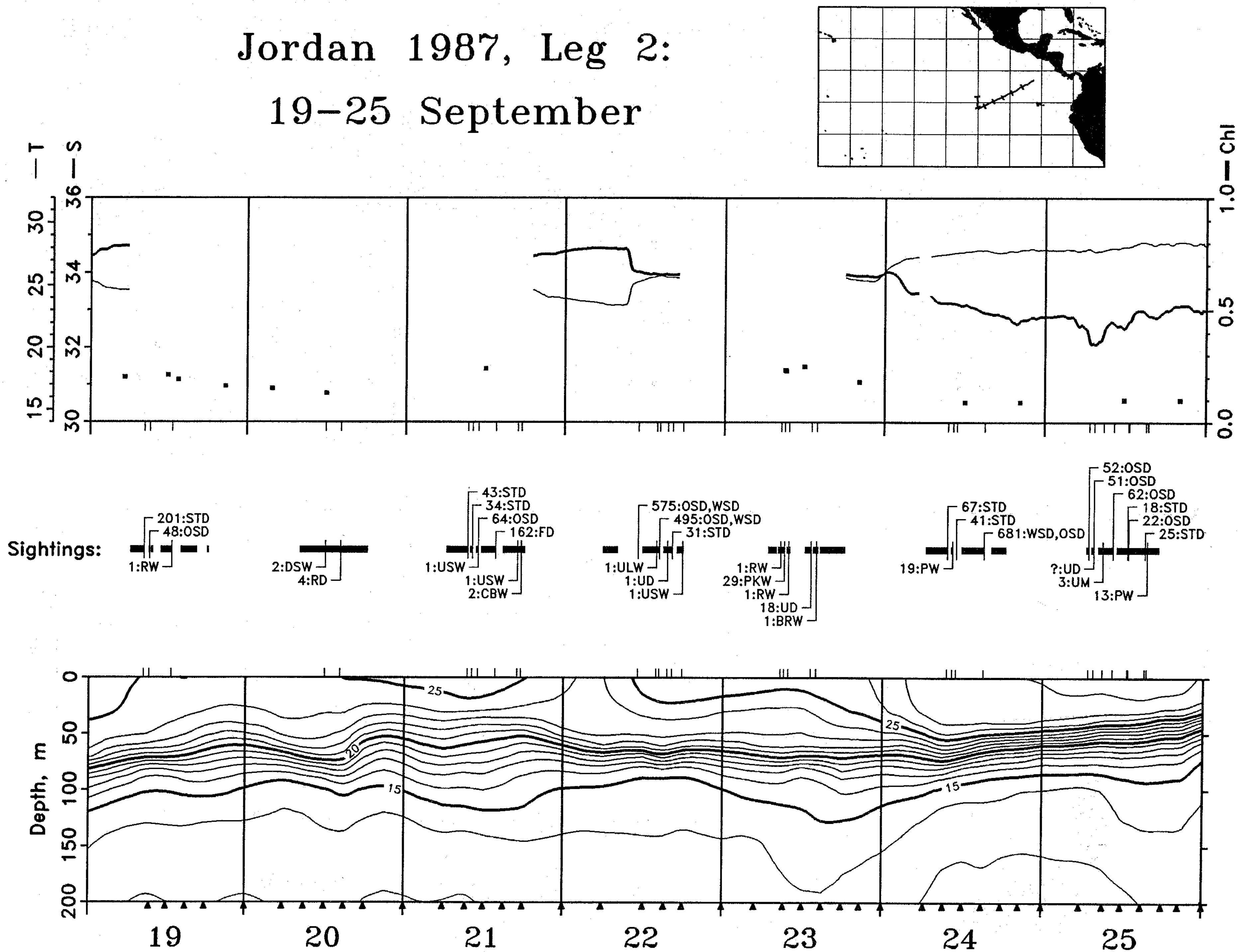
Jordan 1987, Leg 2:
5–11 September



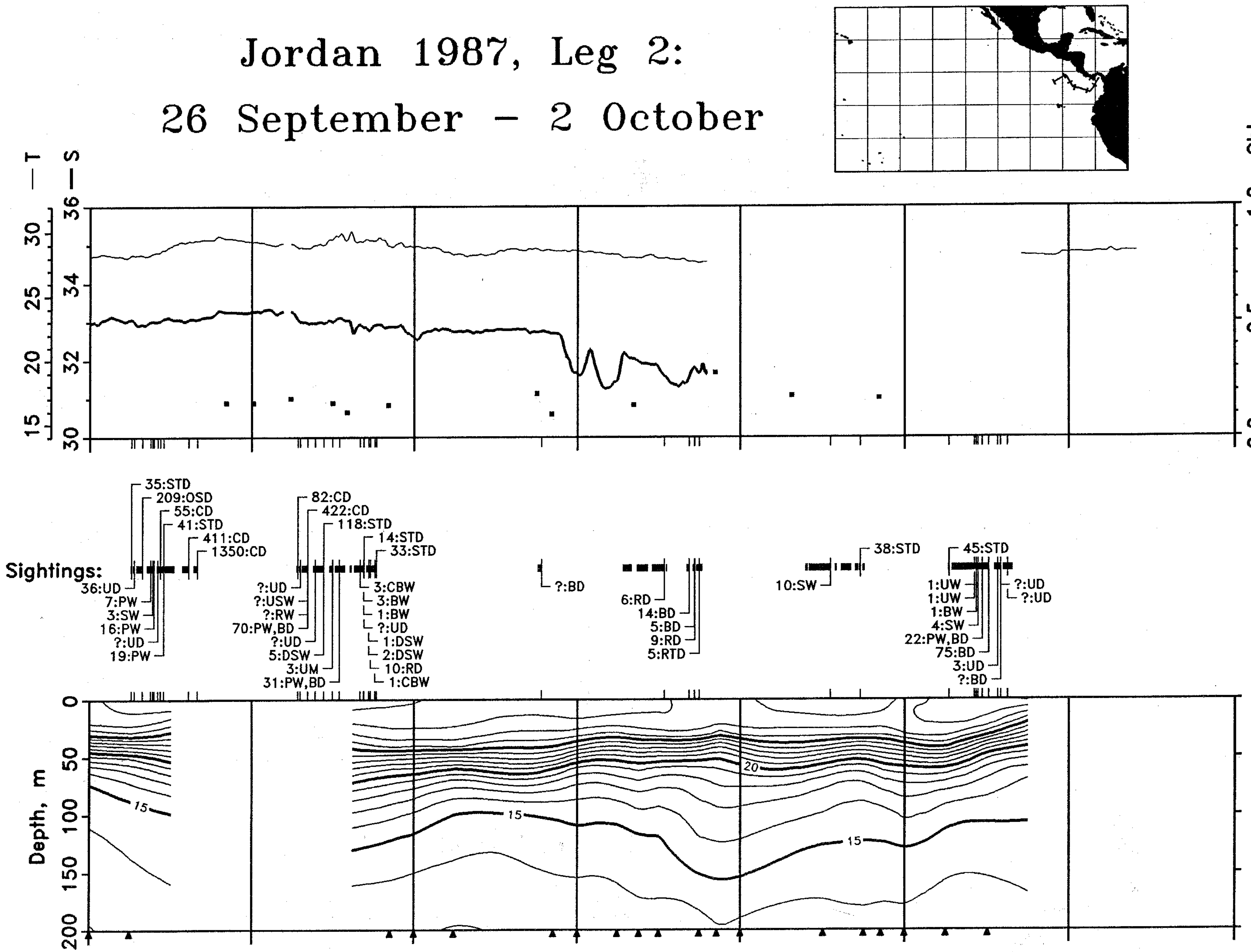
Jordan 1987, Leg 2:
12–18 September



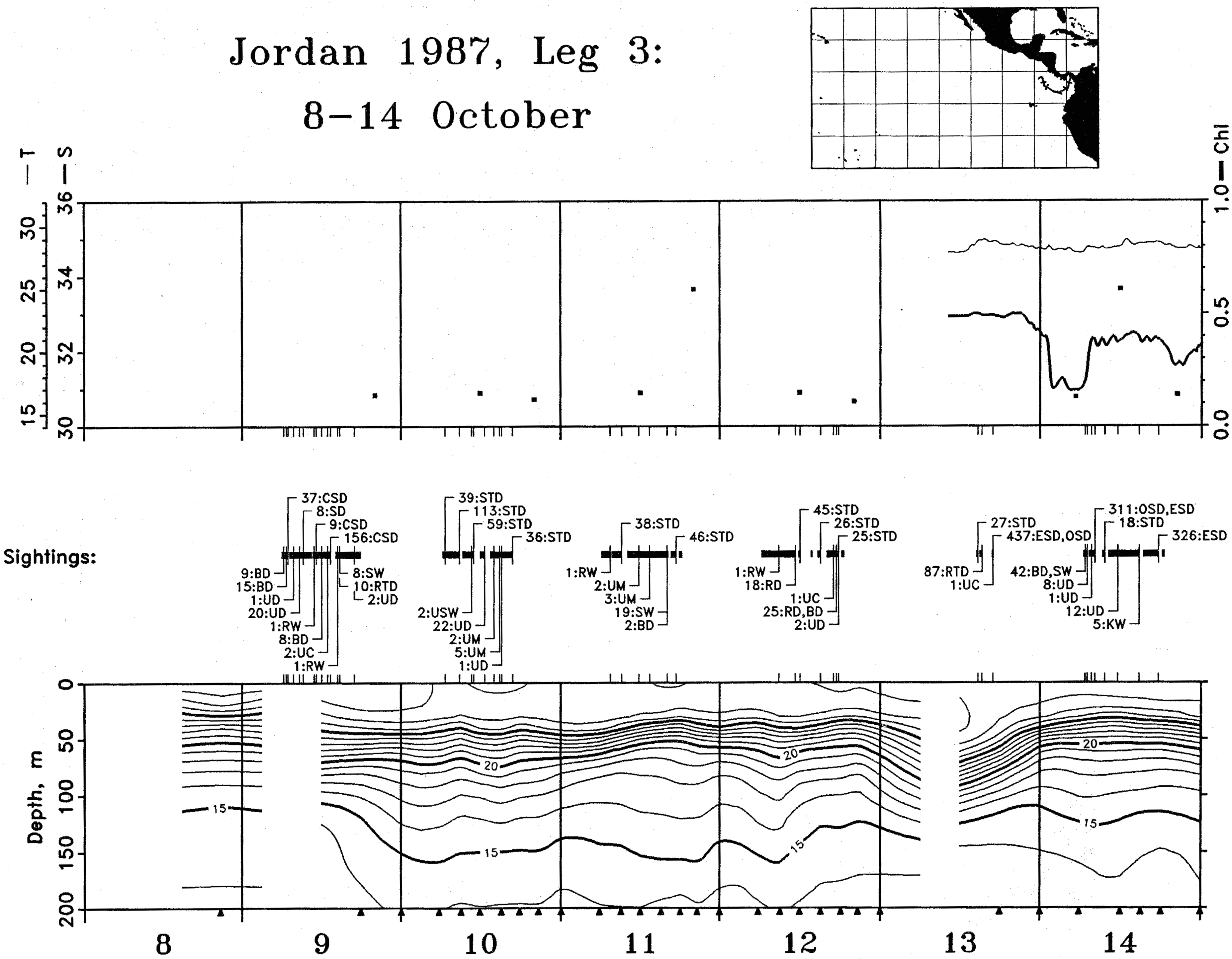
Jordan 1987, Leg 2:
19–25 September



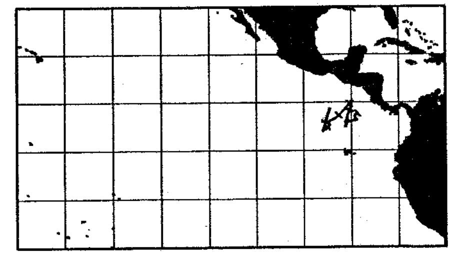
Jordan 1987, Leg 2:
26 September – 2 October

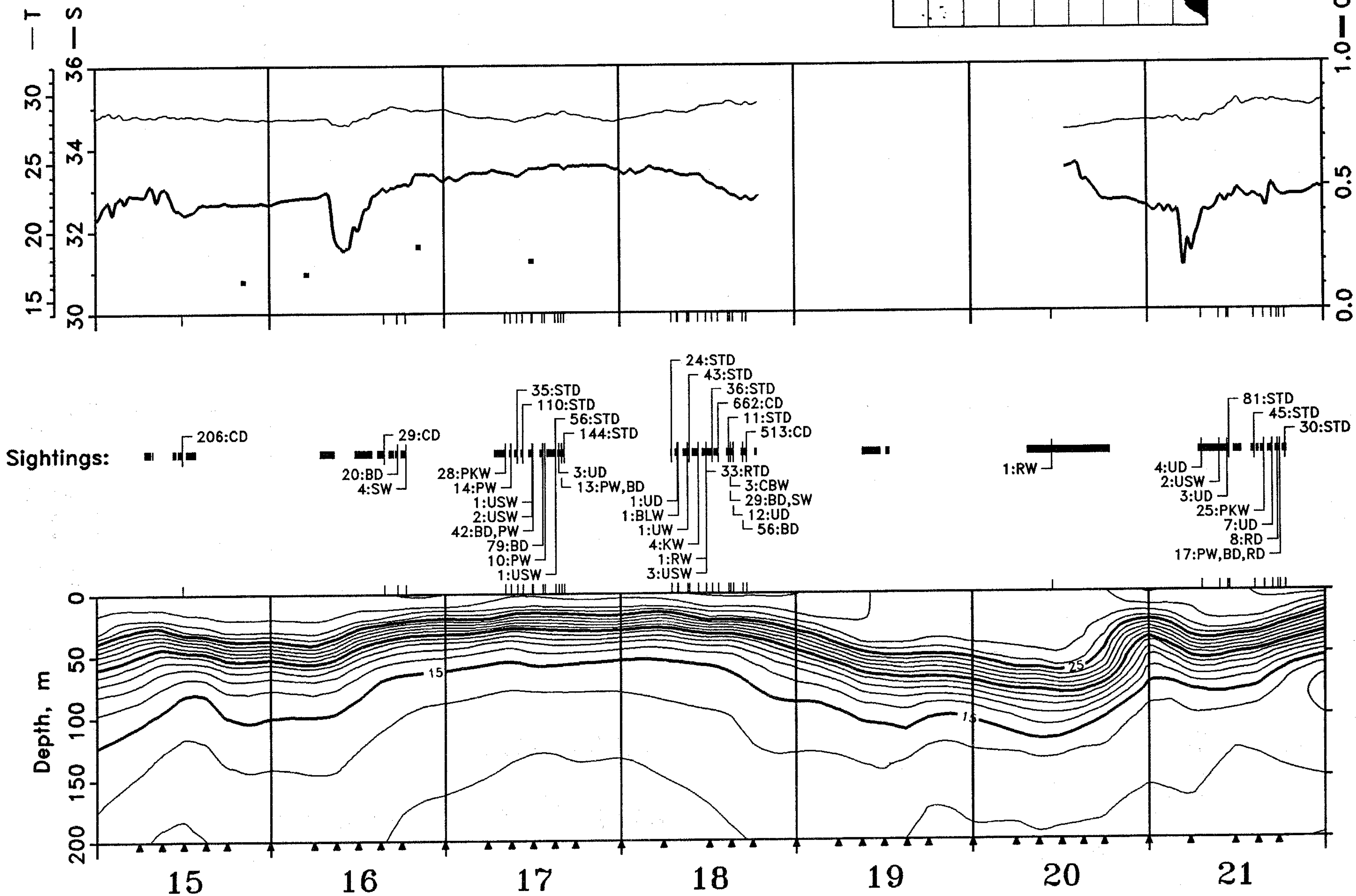


Jordan 1987, Leg 3:
8–14 October

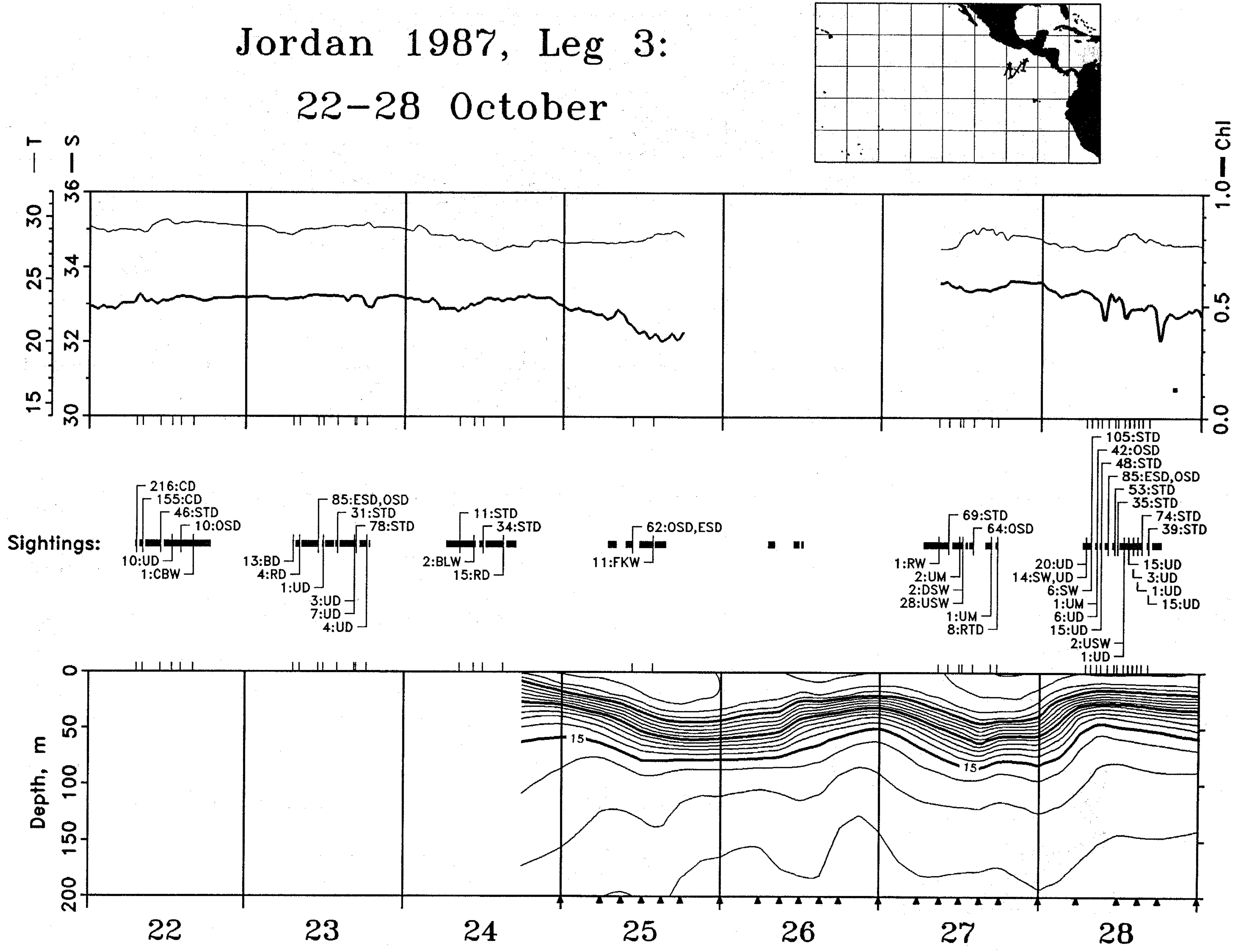


Jordan 1987, Leg 3:
15–21 October

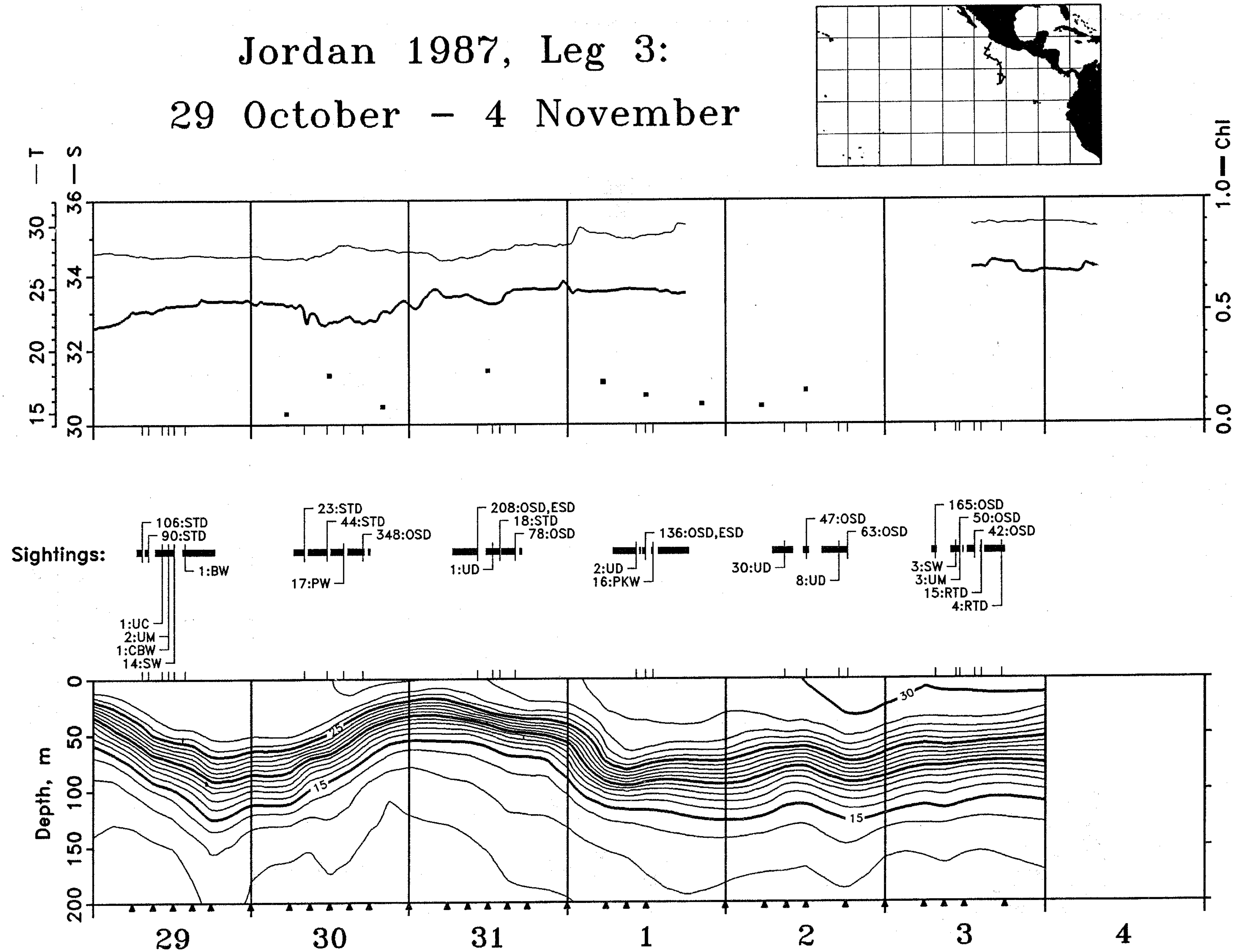




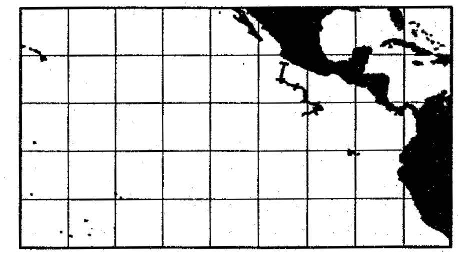
Jordan 1987, Leg 3: 22–28 October

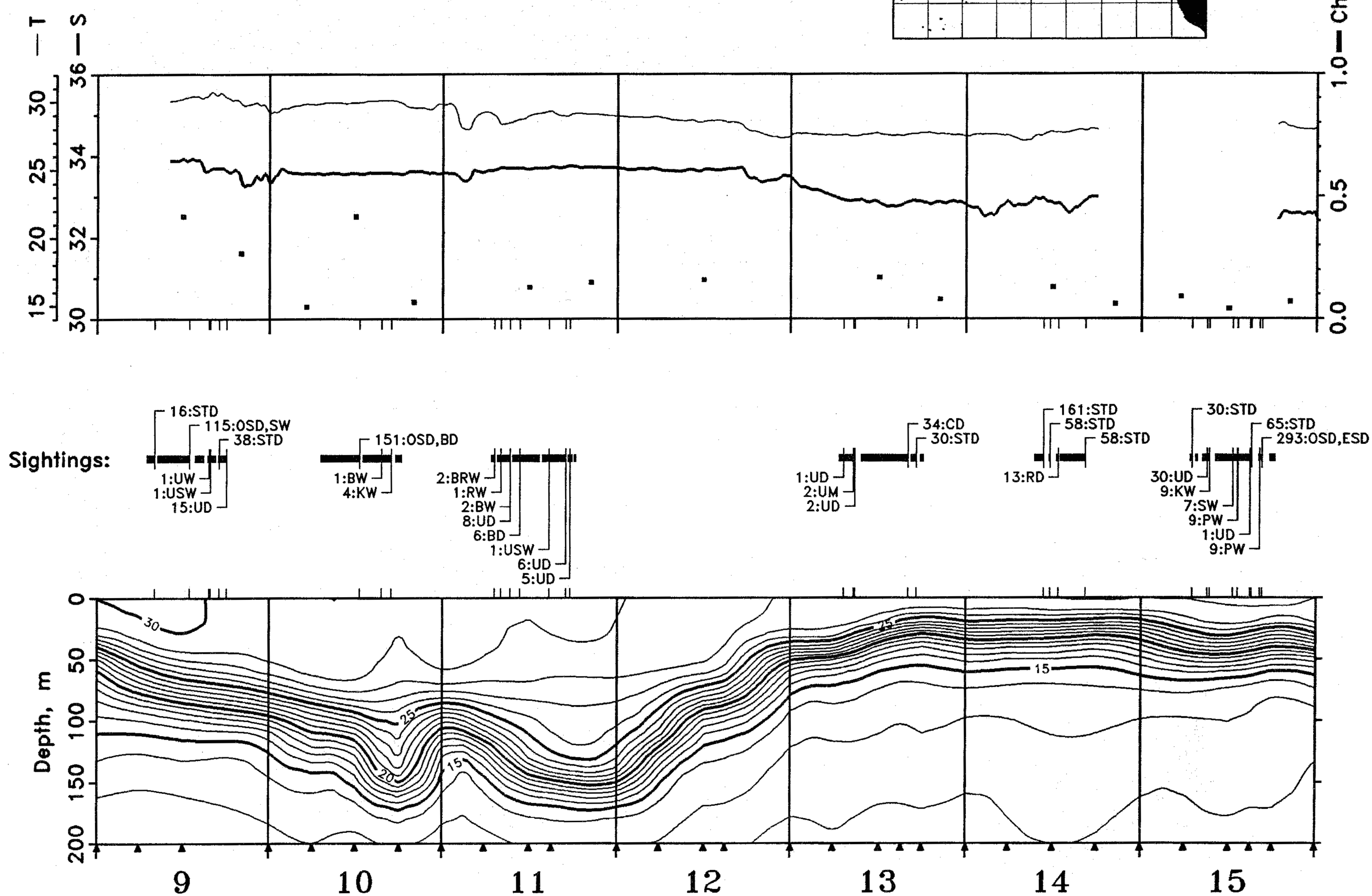


Jordan 1987, Leg 3:
29 October – 4 November

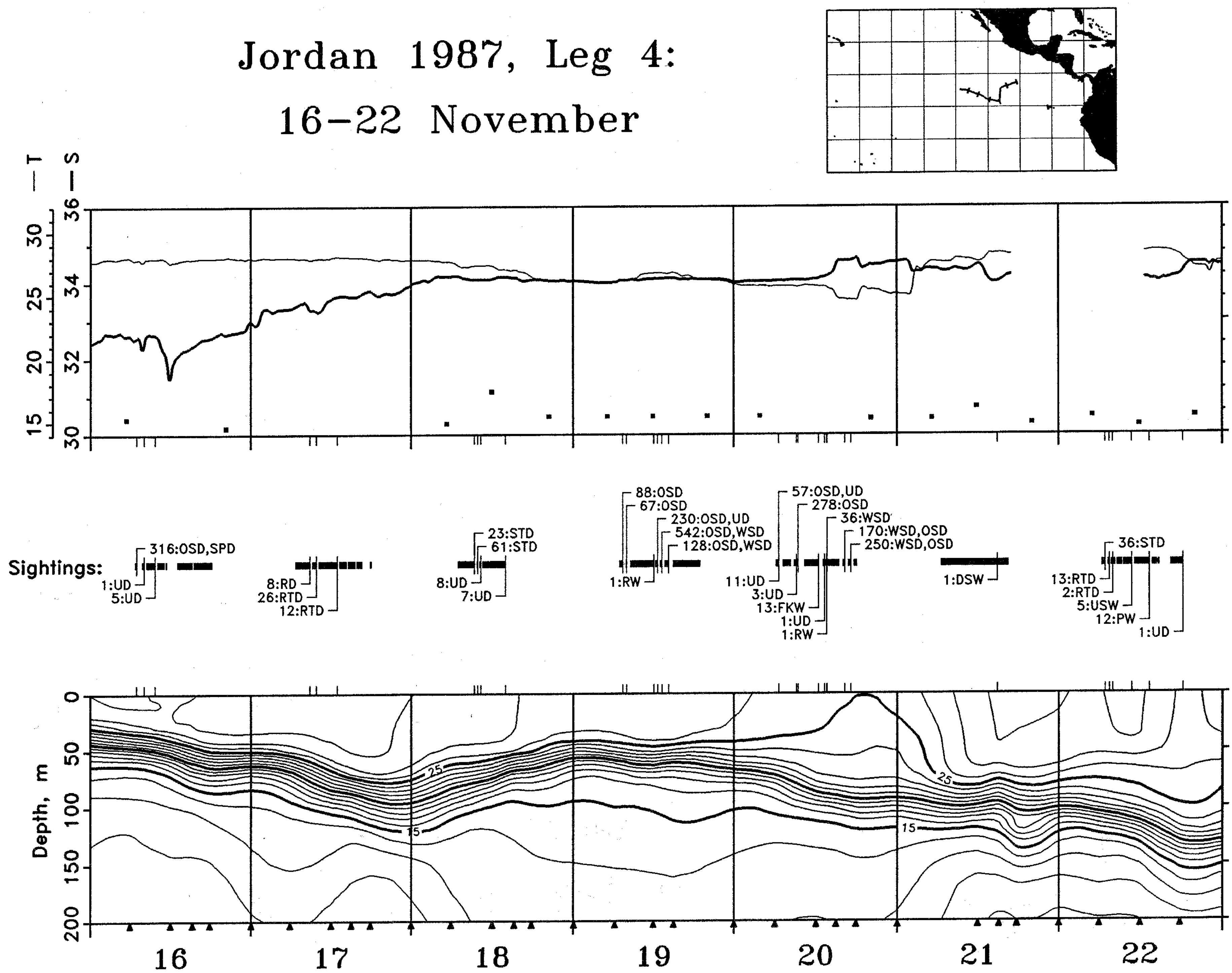


Jordan 1987, Leg 4:
9–15 November

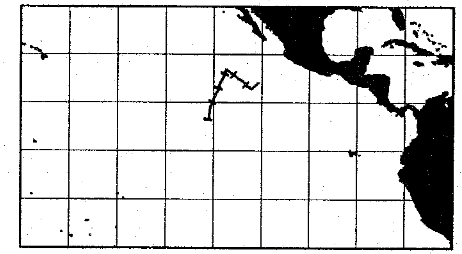


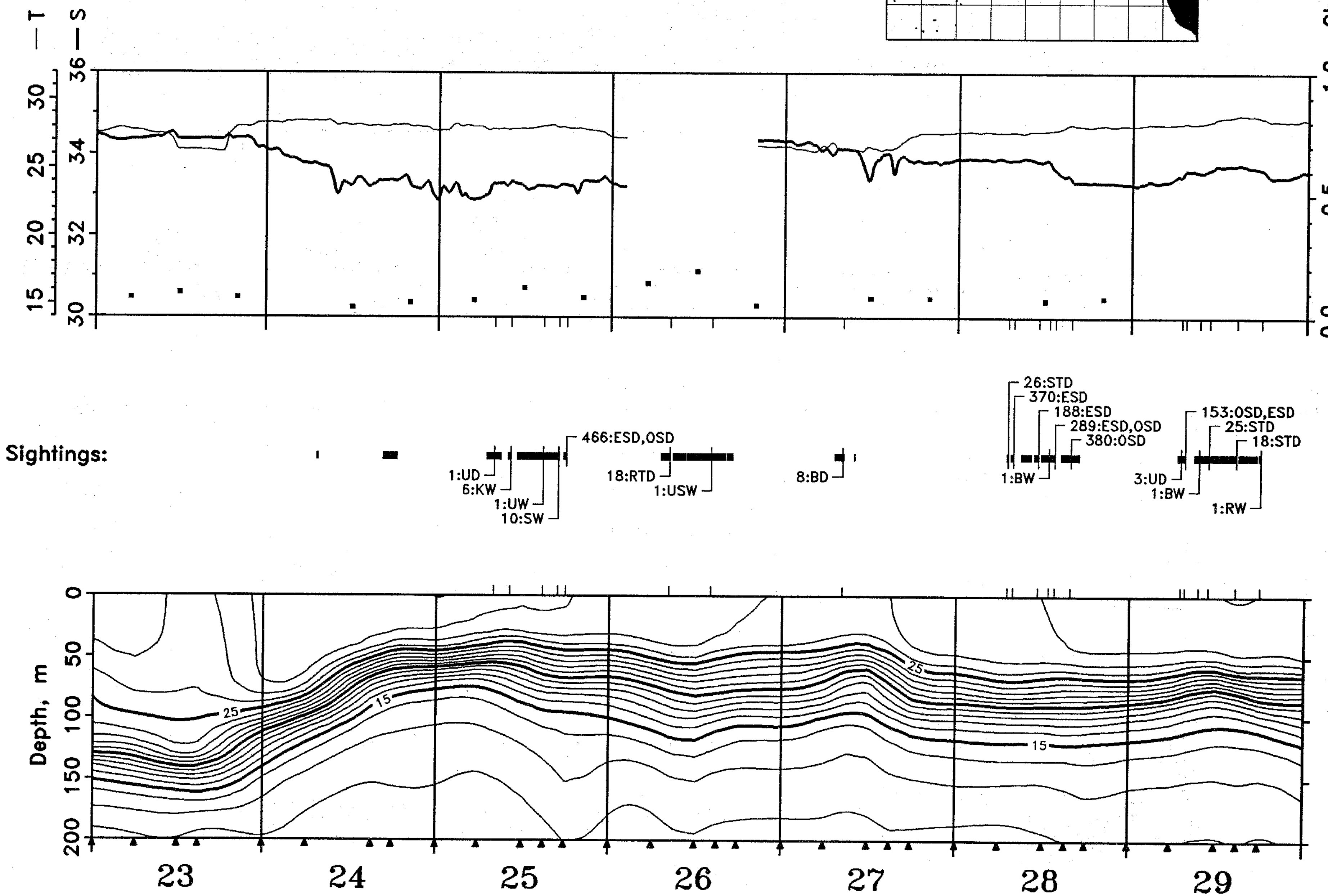


Jordan 1987, Leg 4:
16–22 November

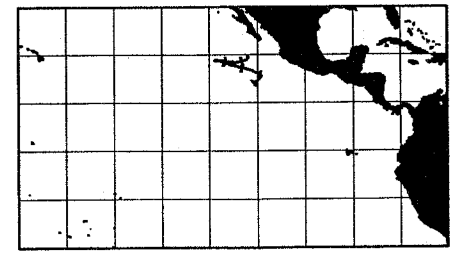


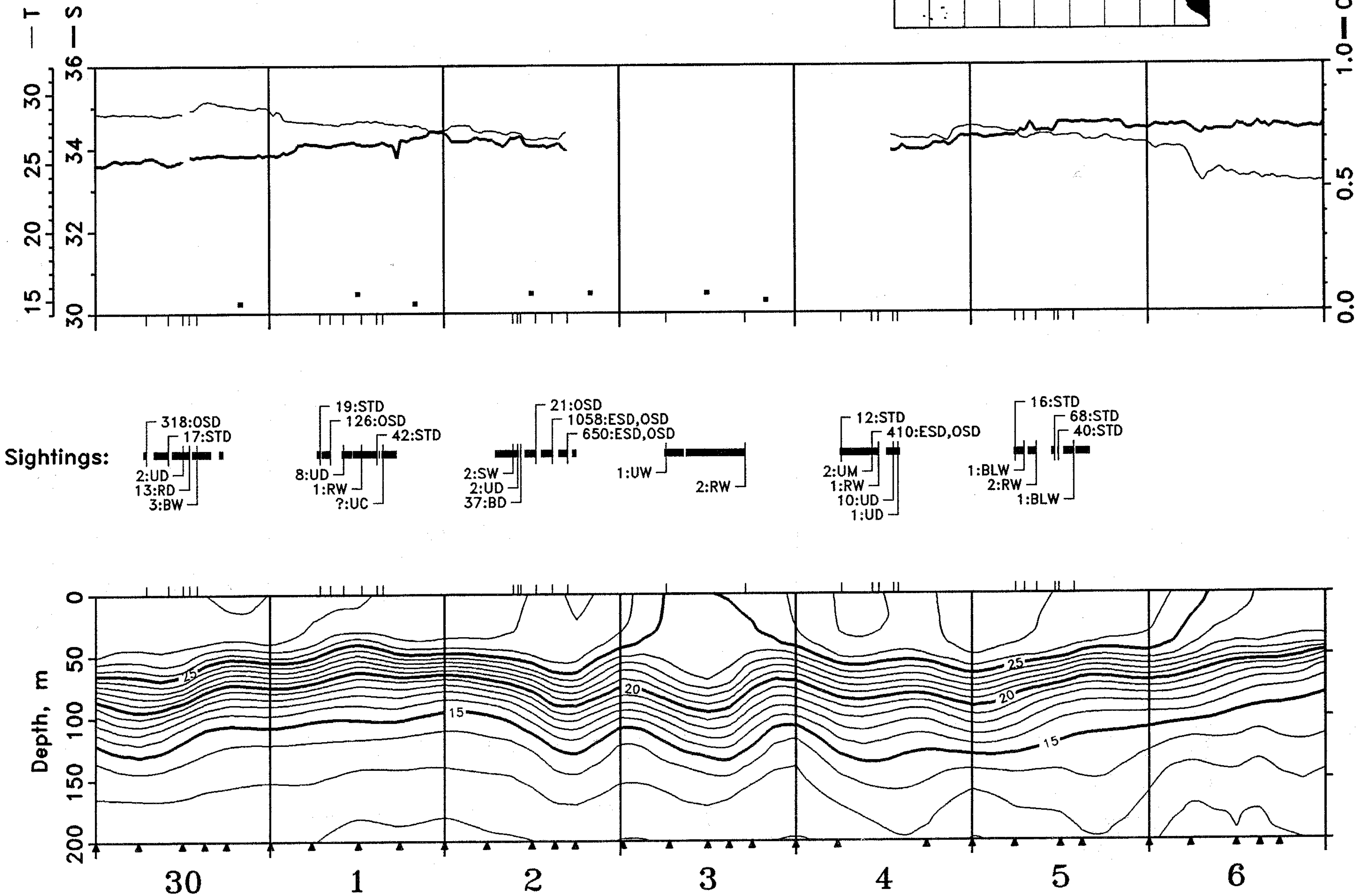
Jordan 1987, Leg 4:
23–29 November



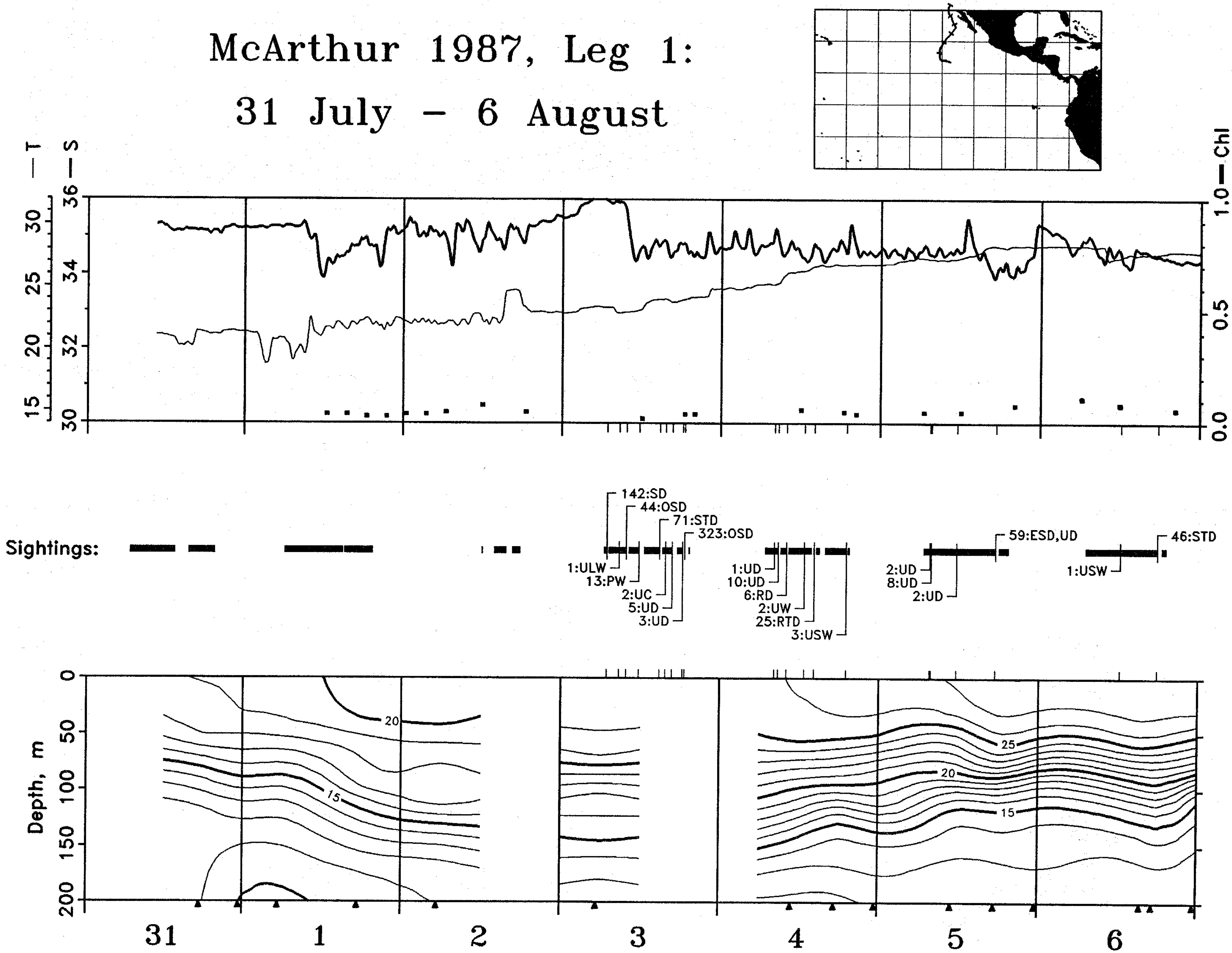


Jordan 1987, Leg 4:
30 November – 6 December

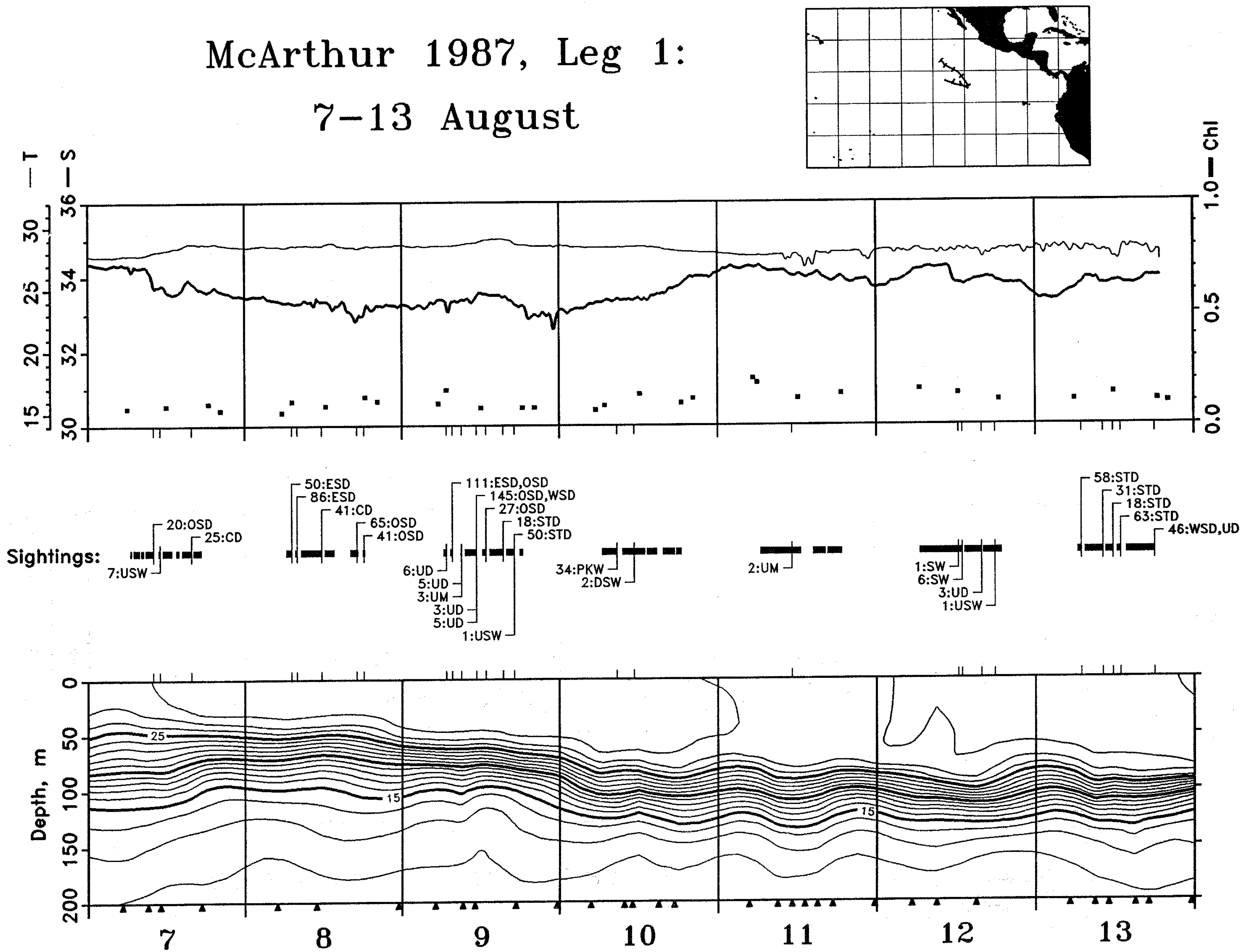




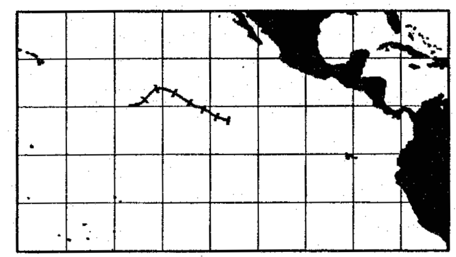
McArthur 1987, Leg 1:
31 July – 6 August

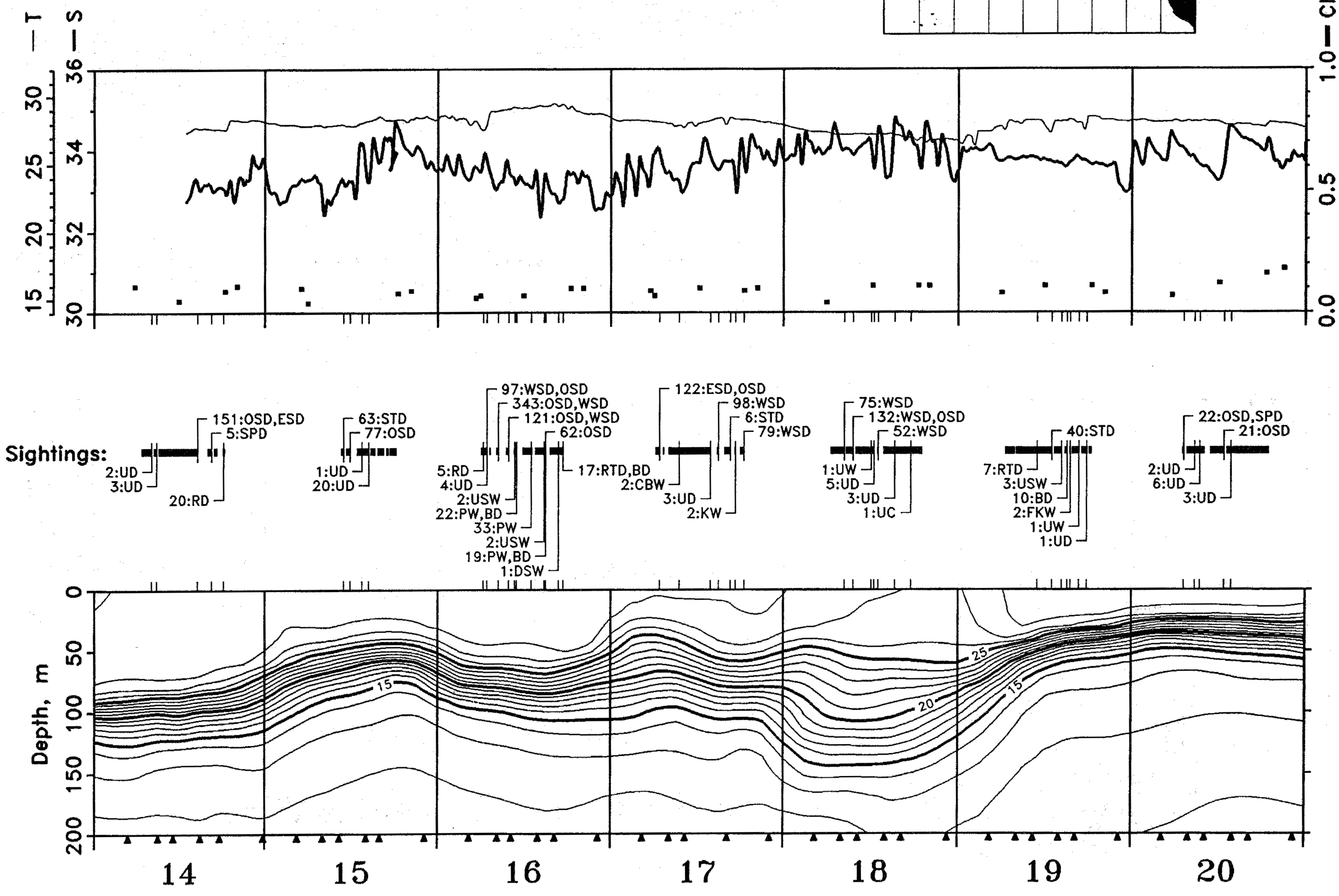


McArthur 1987, Leg 1:
7–13 August

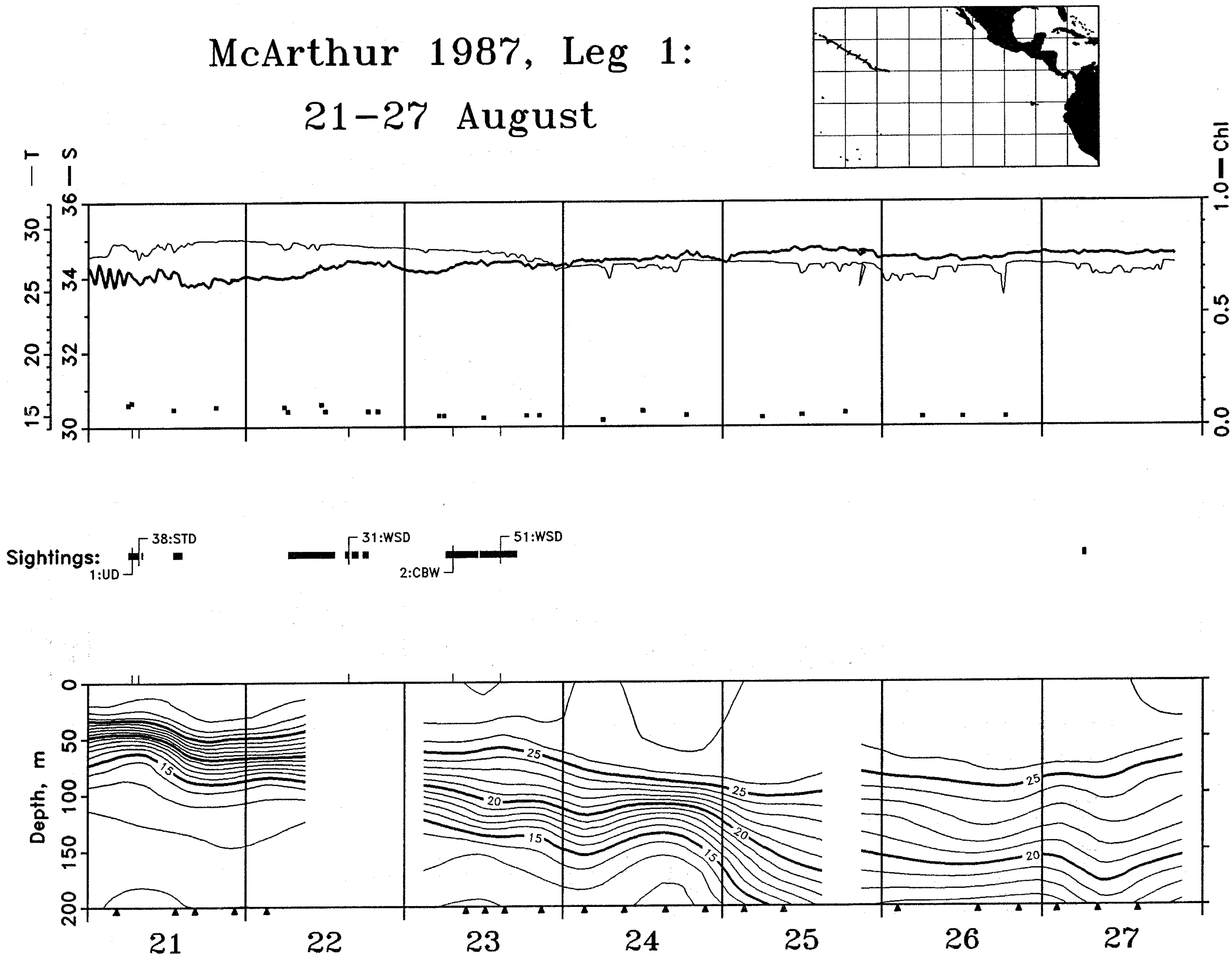


McArthur 1987, Leg 1:
14–20 August

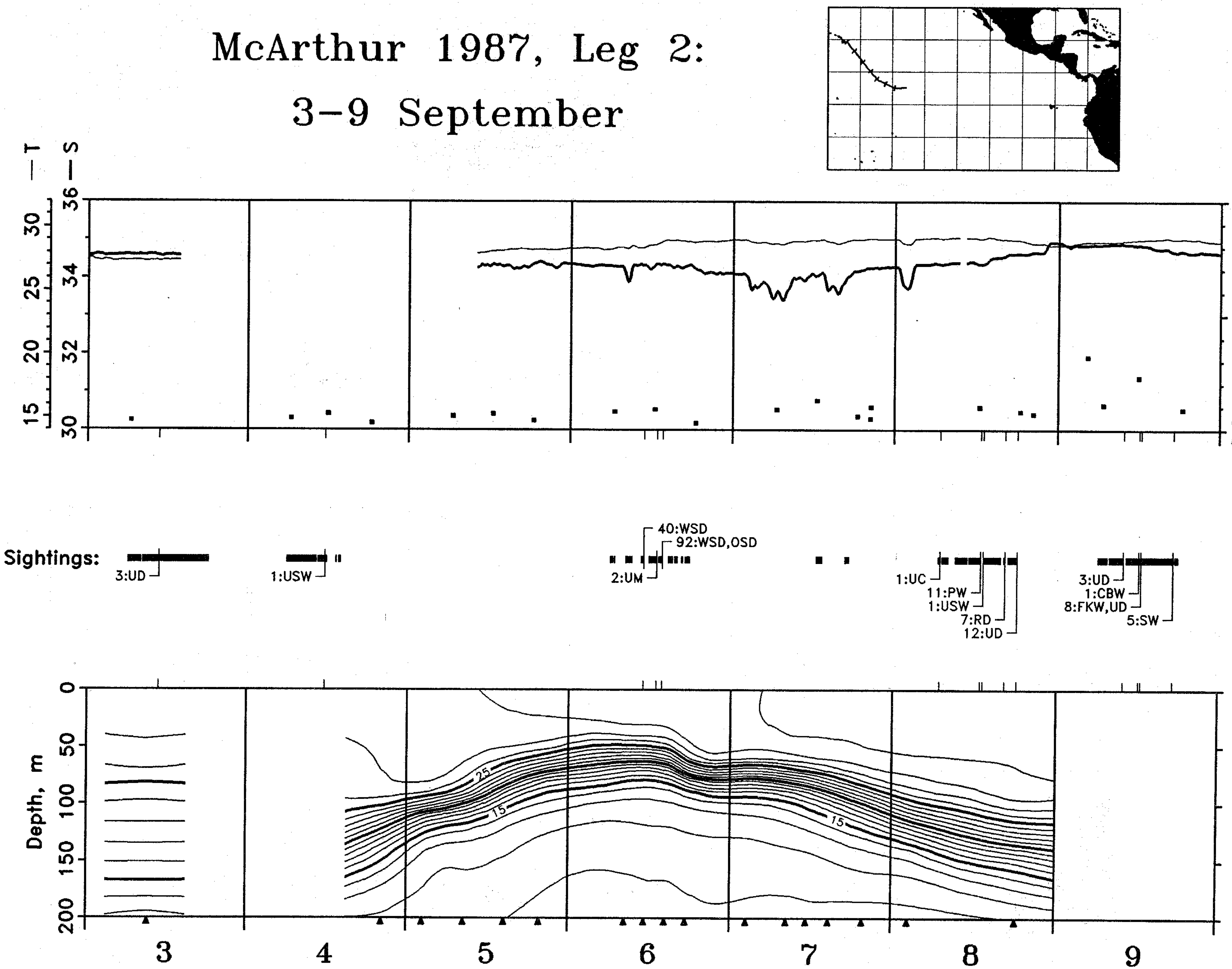




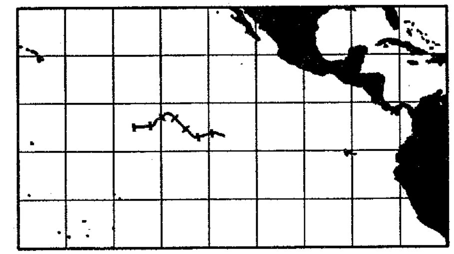
McArthur 1987, Leg 1:
21–27 August

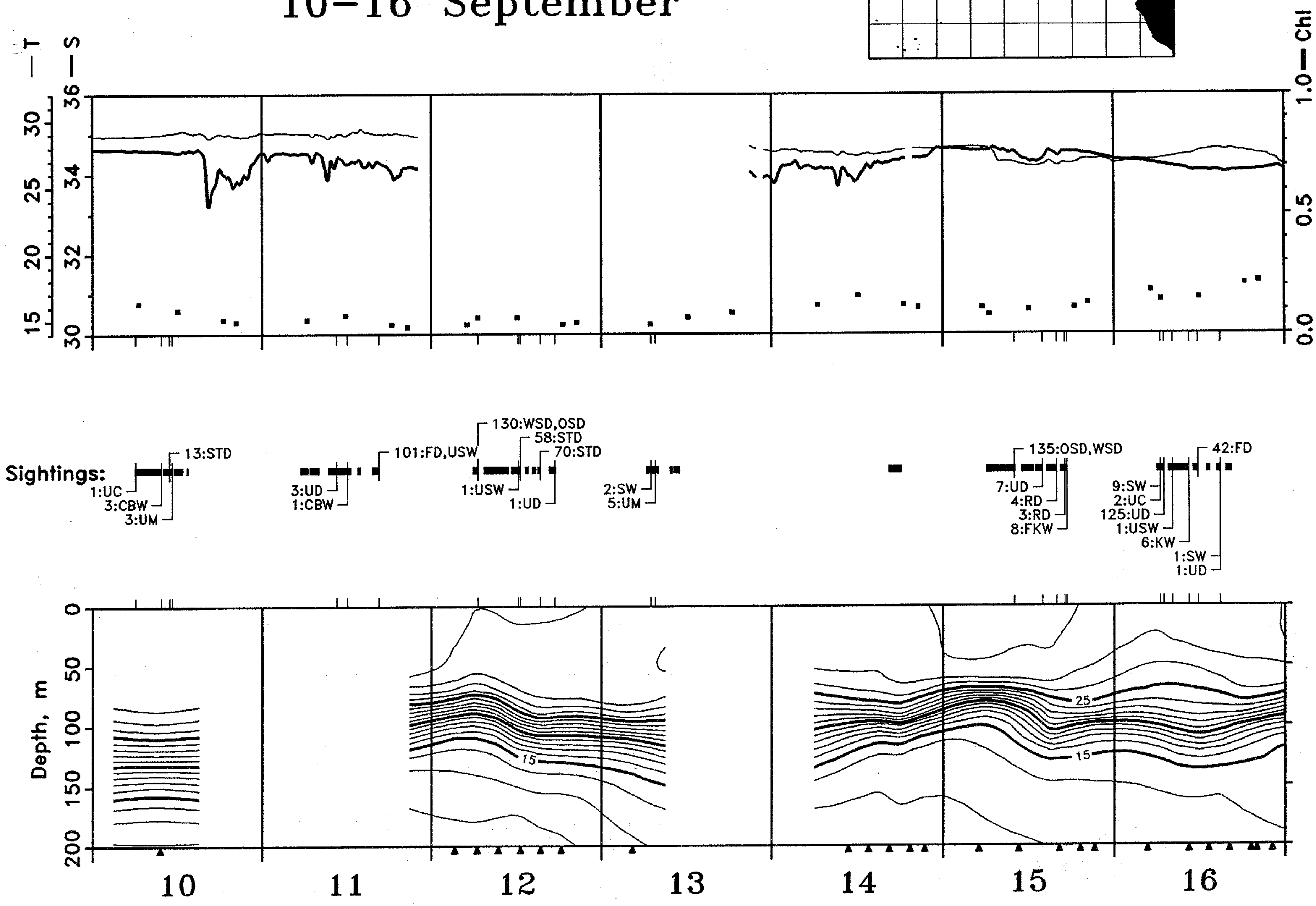


McArthur 1987, Leg 2:
3–9 September

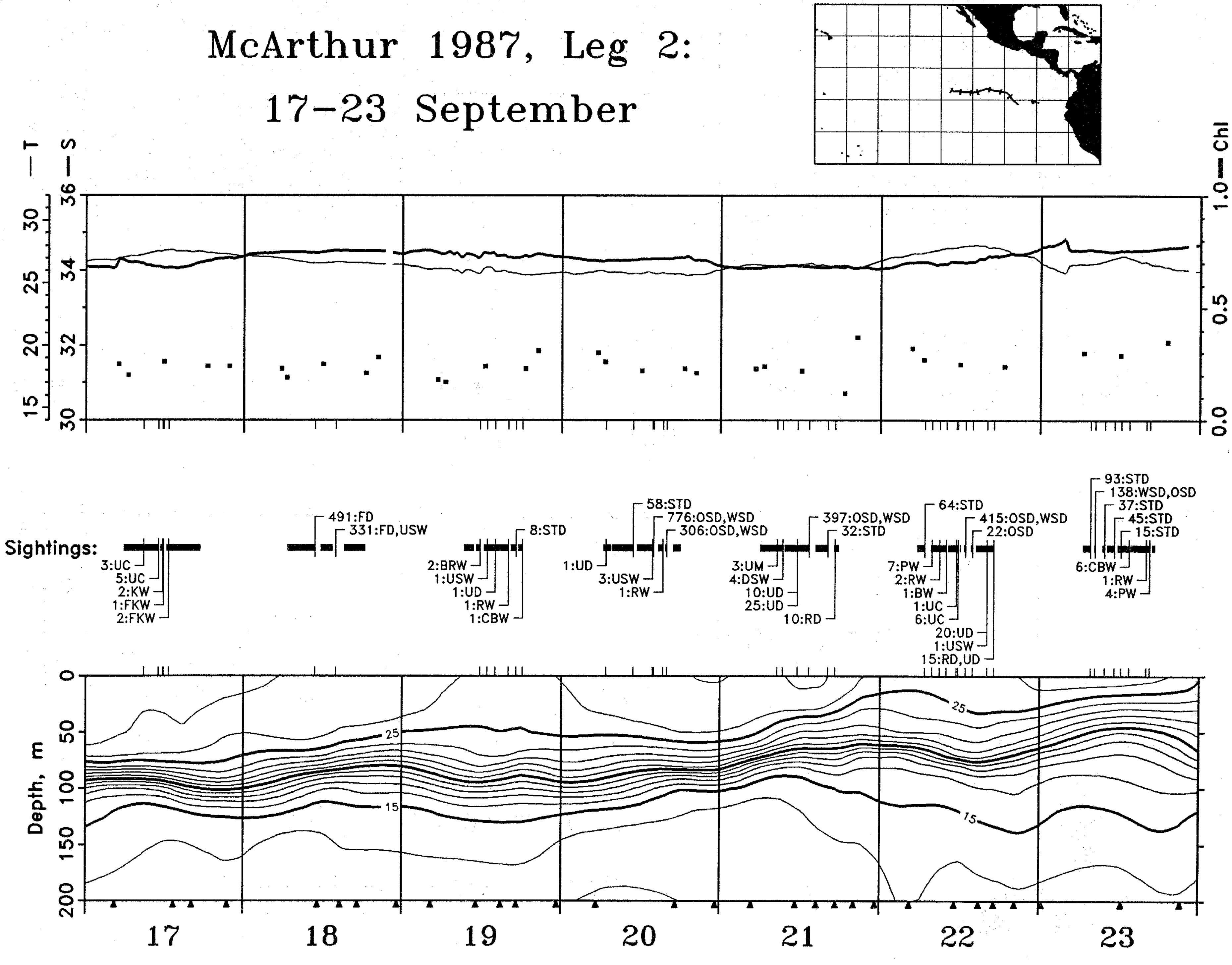


McArthur 1987, Leg 2:
10–16 September

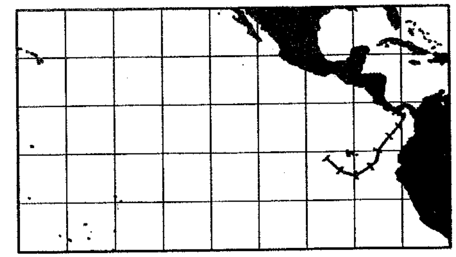


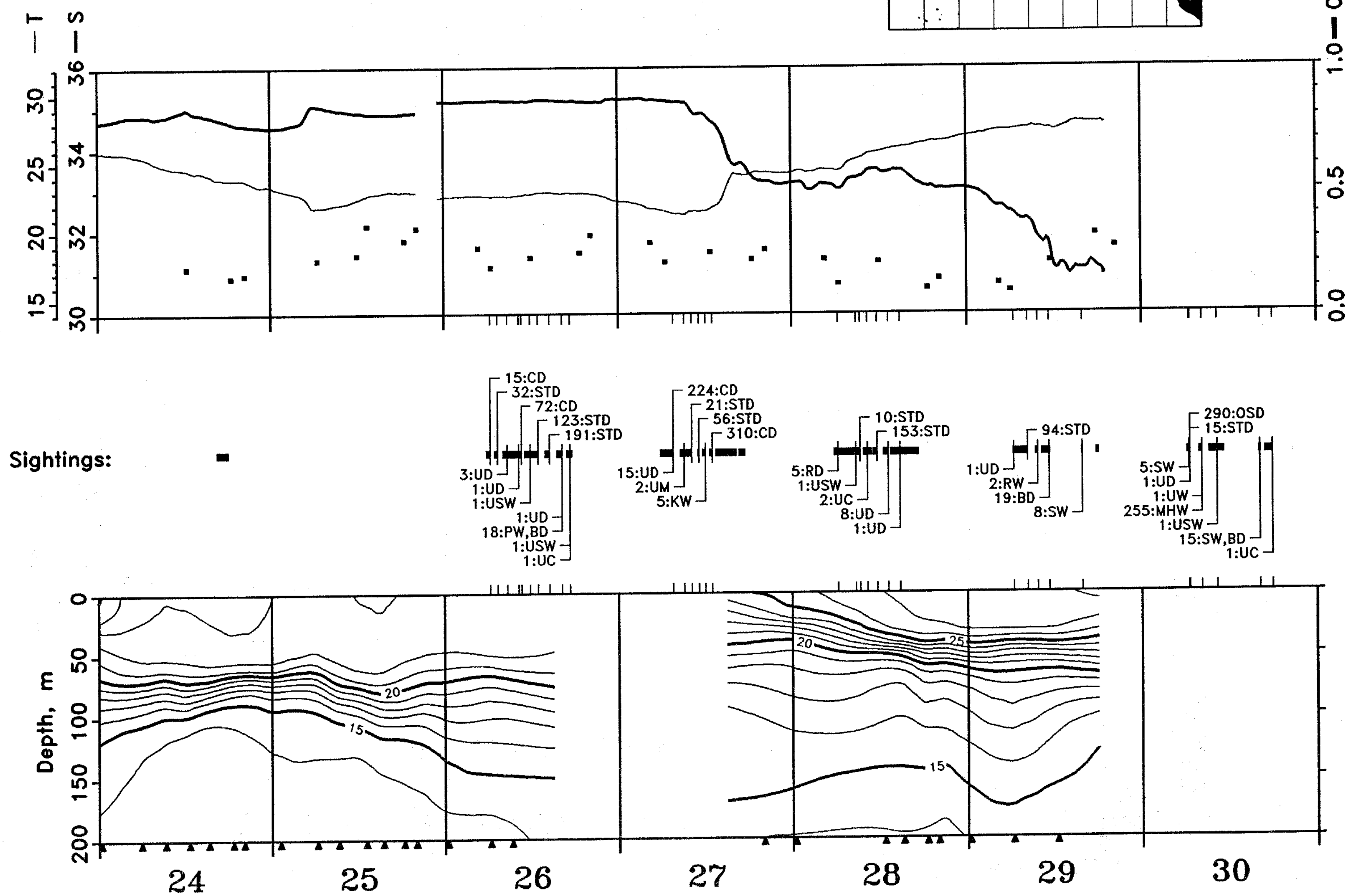


McArthur 1987, Leg 2:
17–23 September

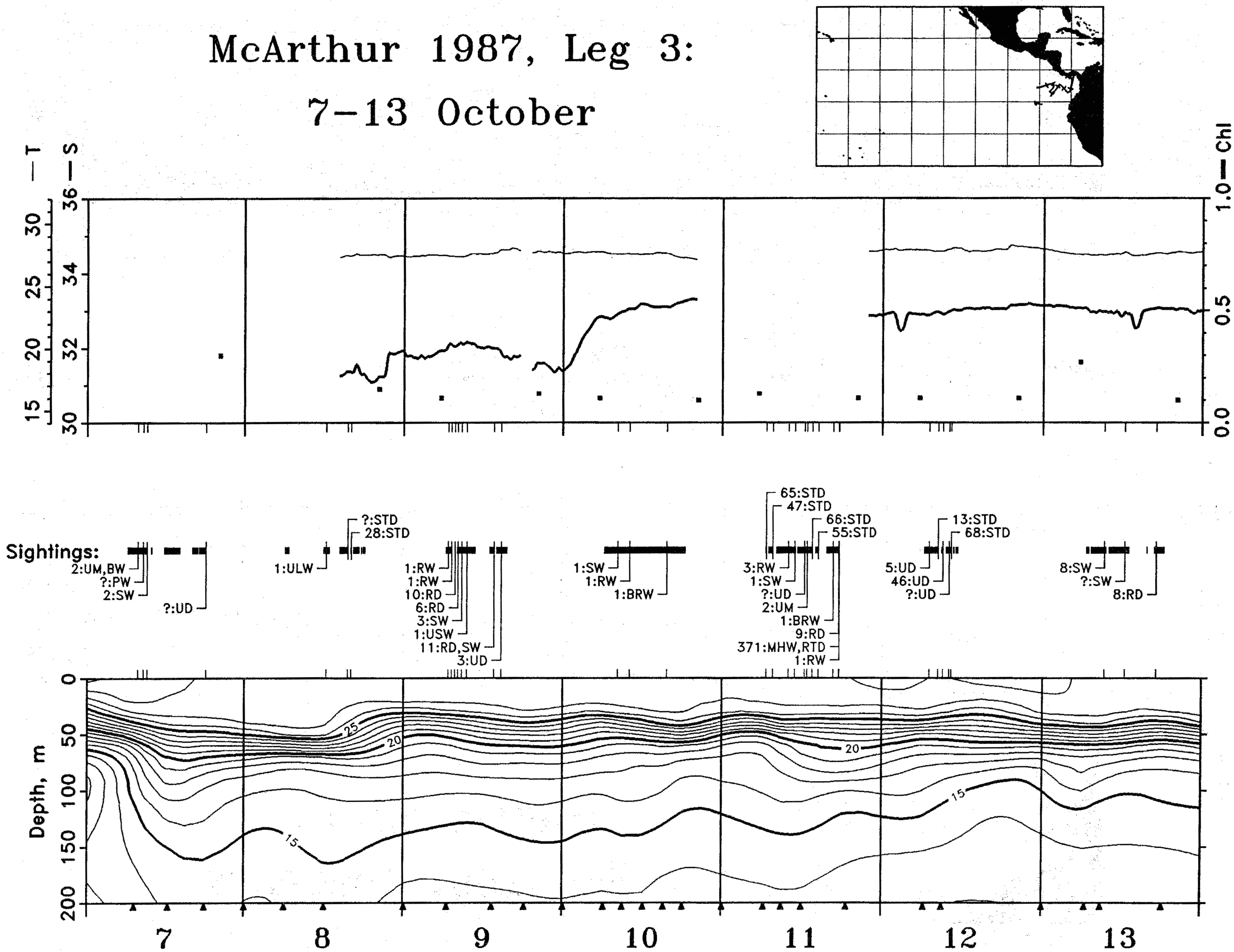


McArthur 1987, Leg 2:
24–30 September

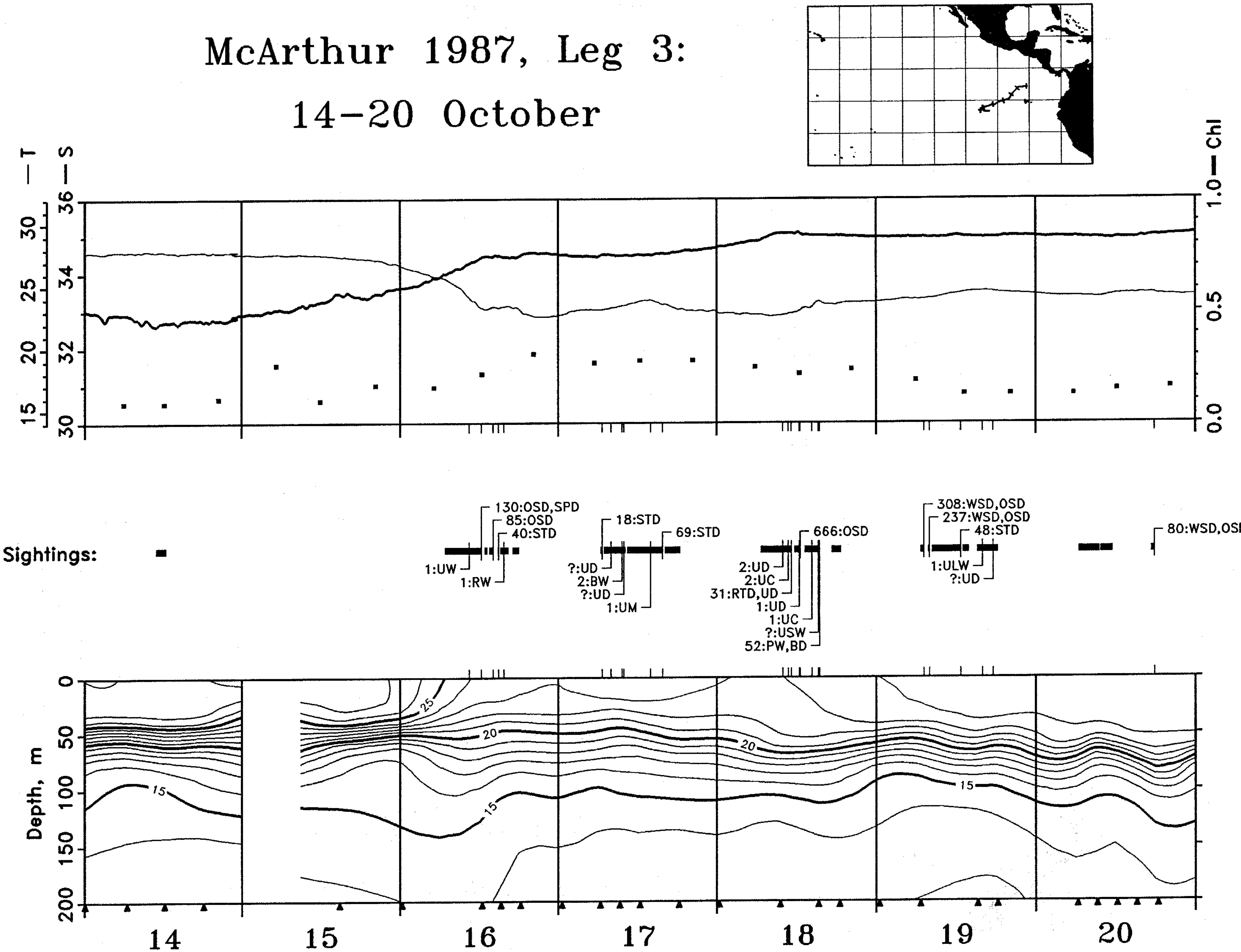




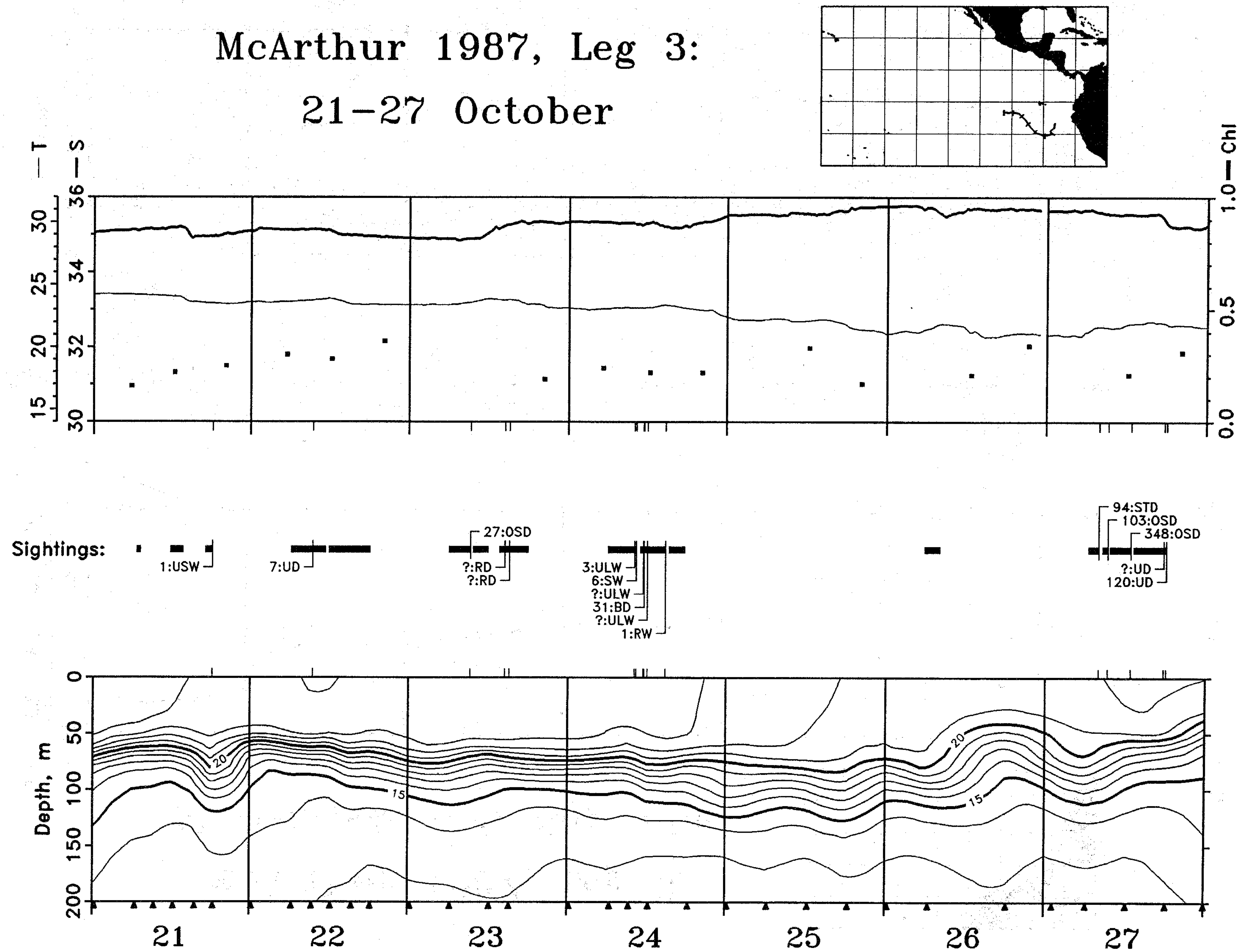
McArthur 1987, Leg 3:
7–13 October



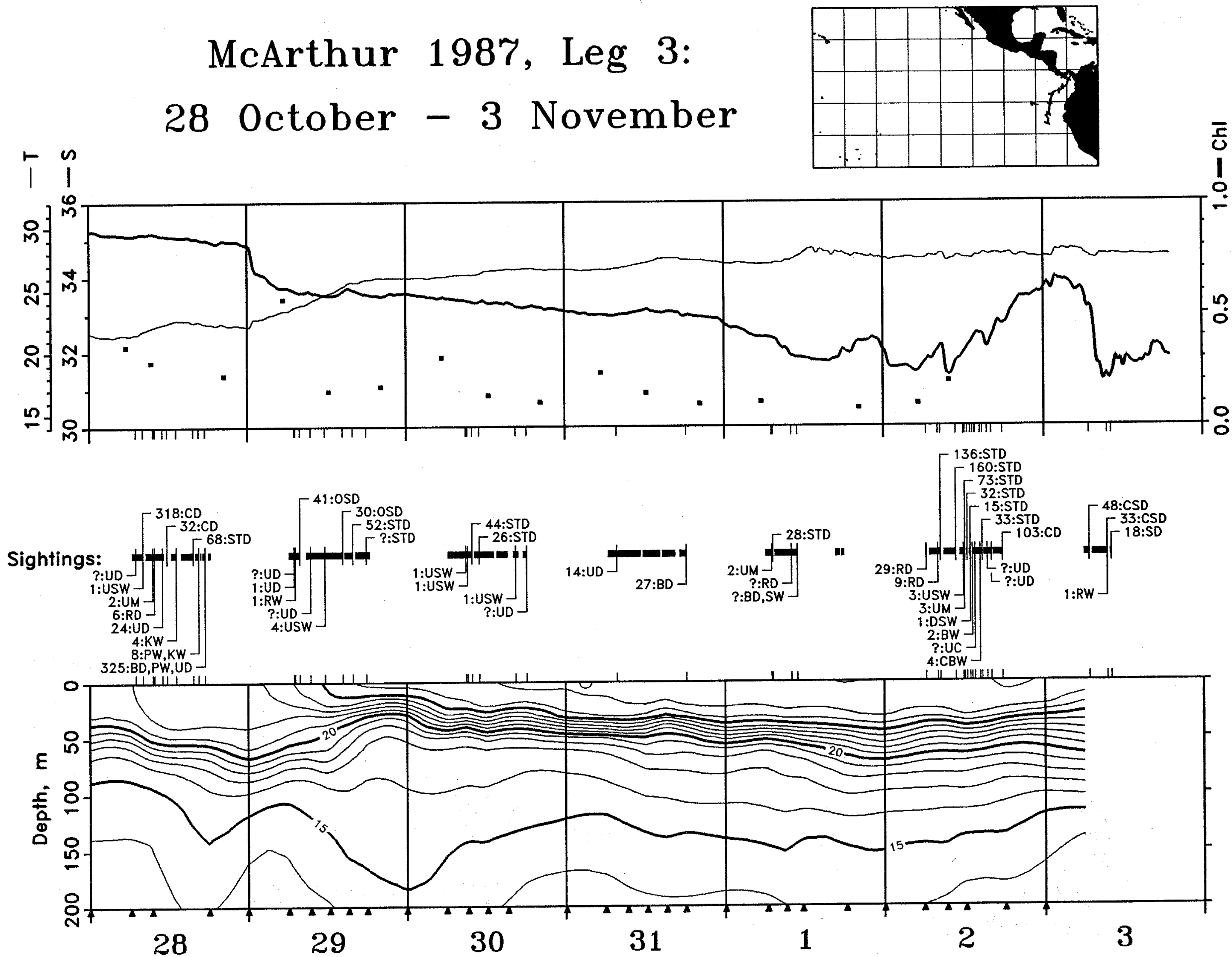
McArthur 1987, Leg 3:
14–20 October



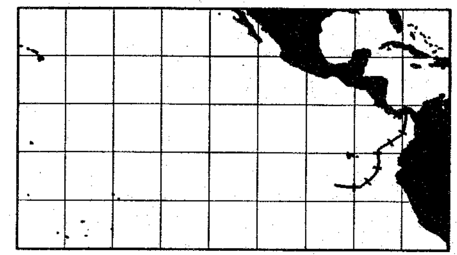
McArthur 1987, Leg 3: 21–27 October

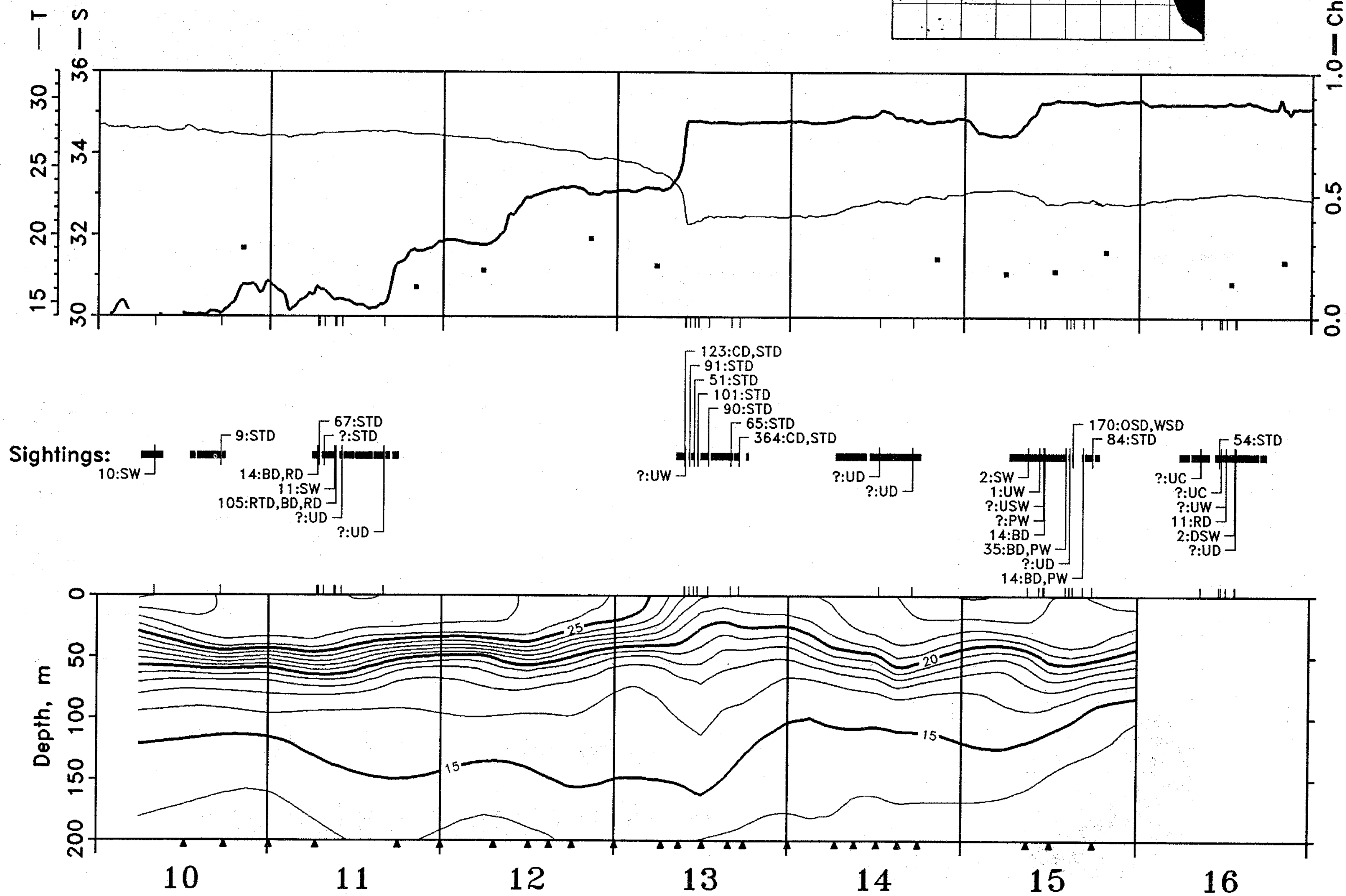


McArthur 1987, Leg 3:
28 October – 3 November

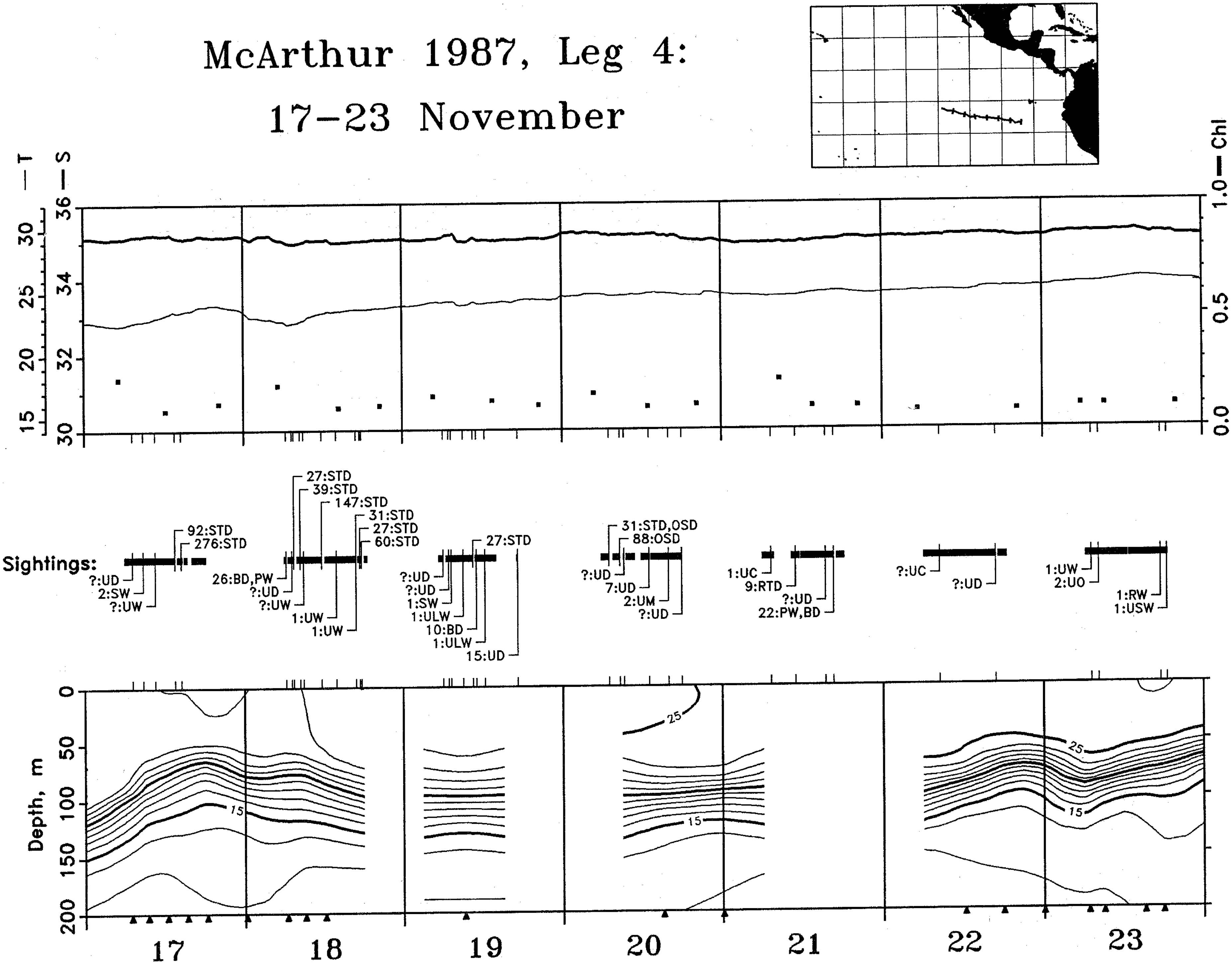


McArthur 1987, Leg 4:
10–16 November

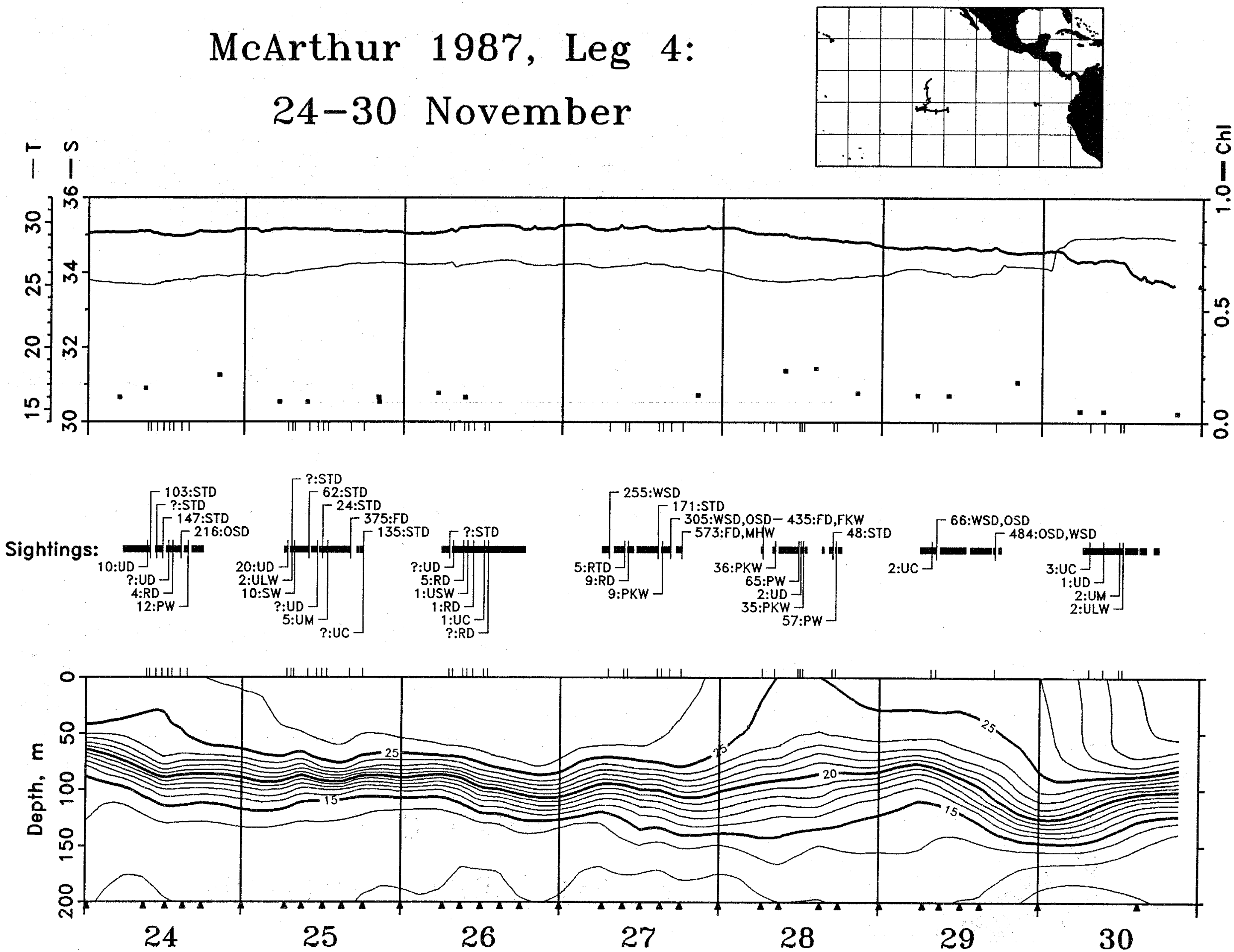




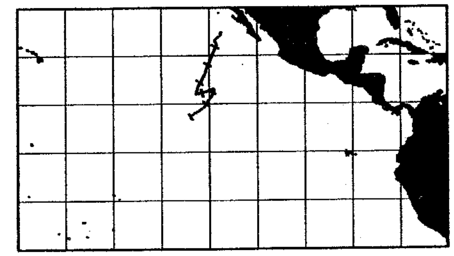
McArthur 1987, Leg 4: 17–23 November

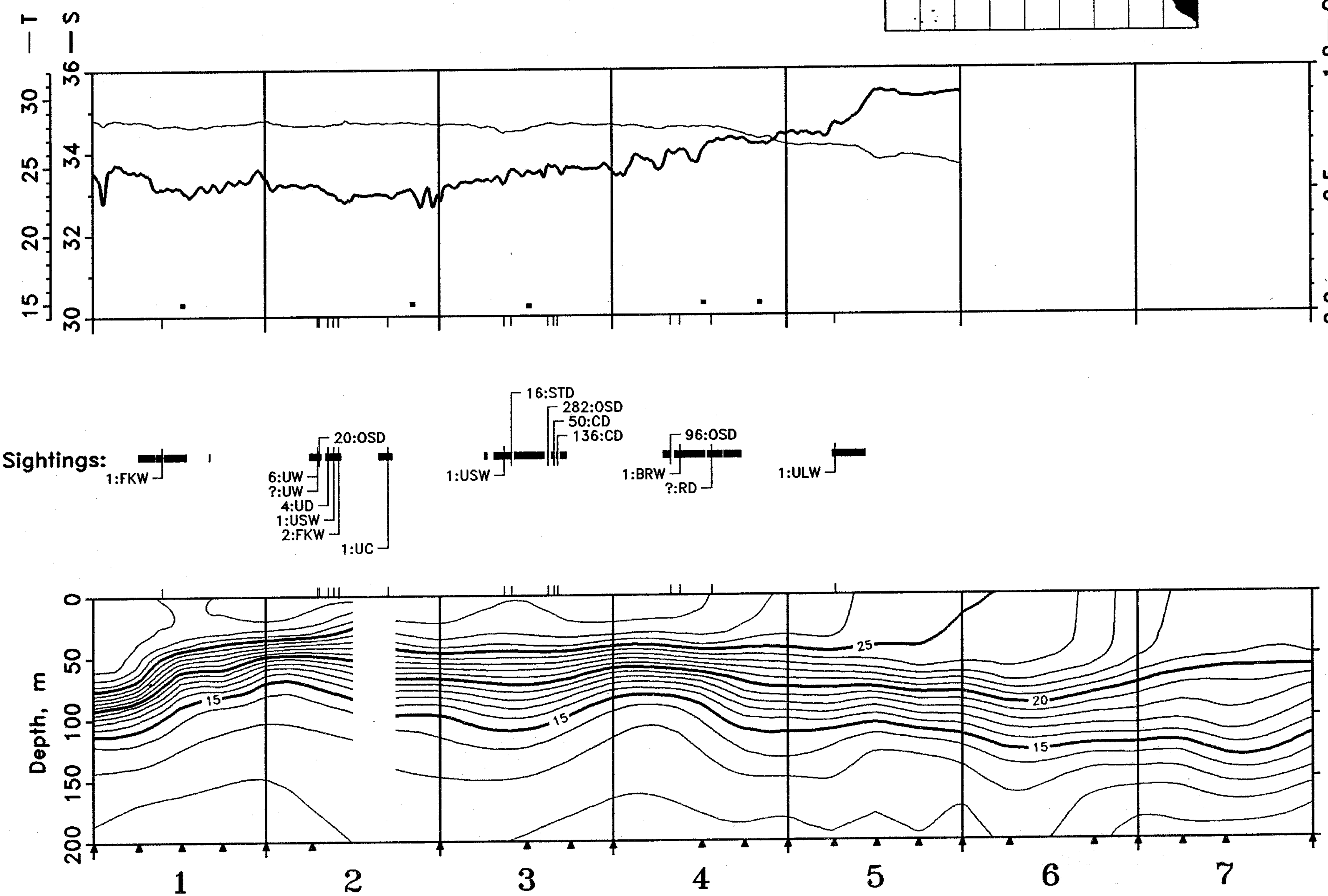


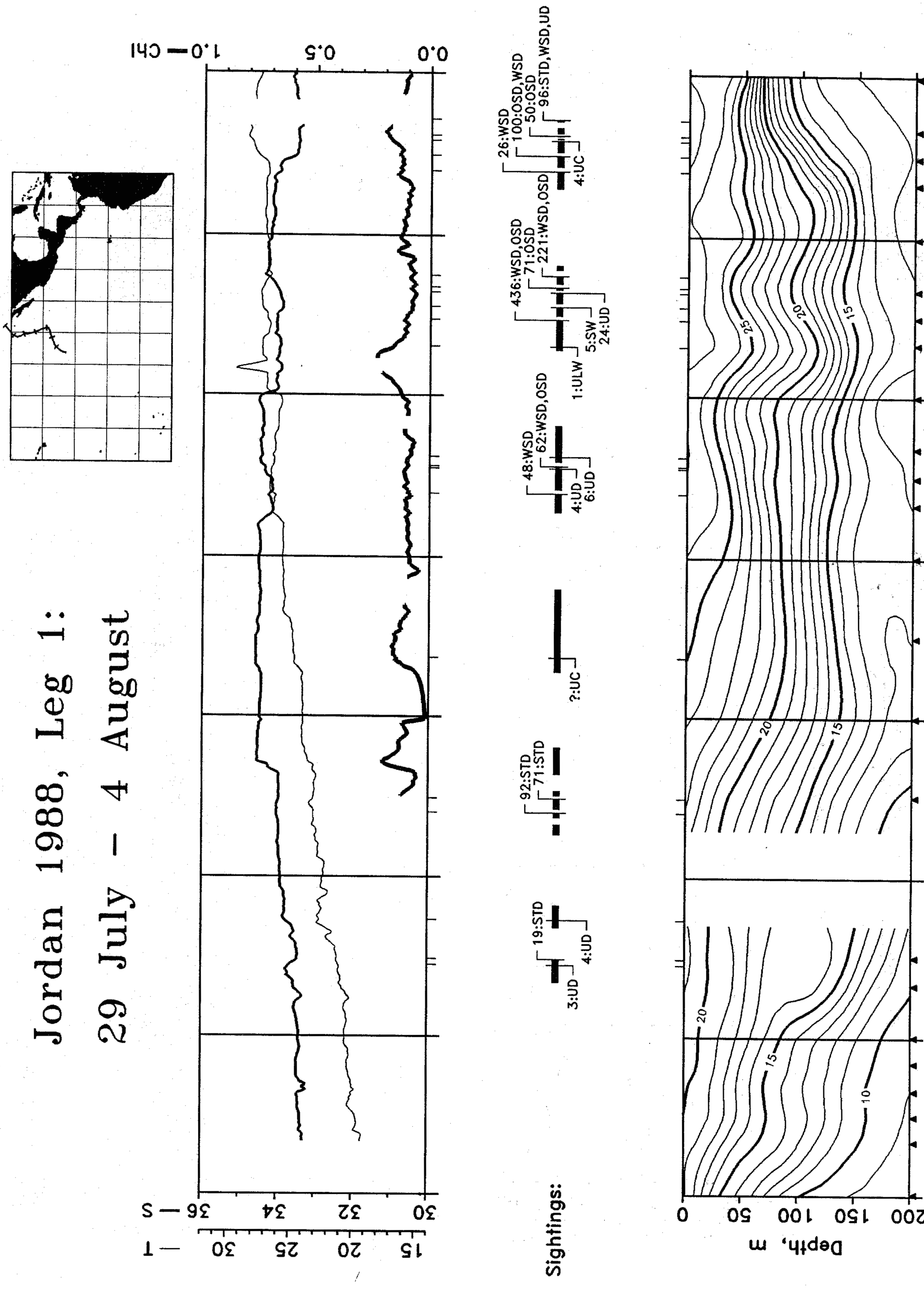
McArthur 1987, Leg 4:
24–30 November



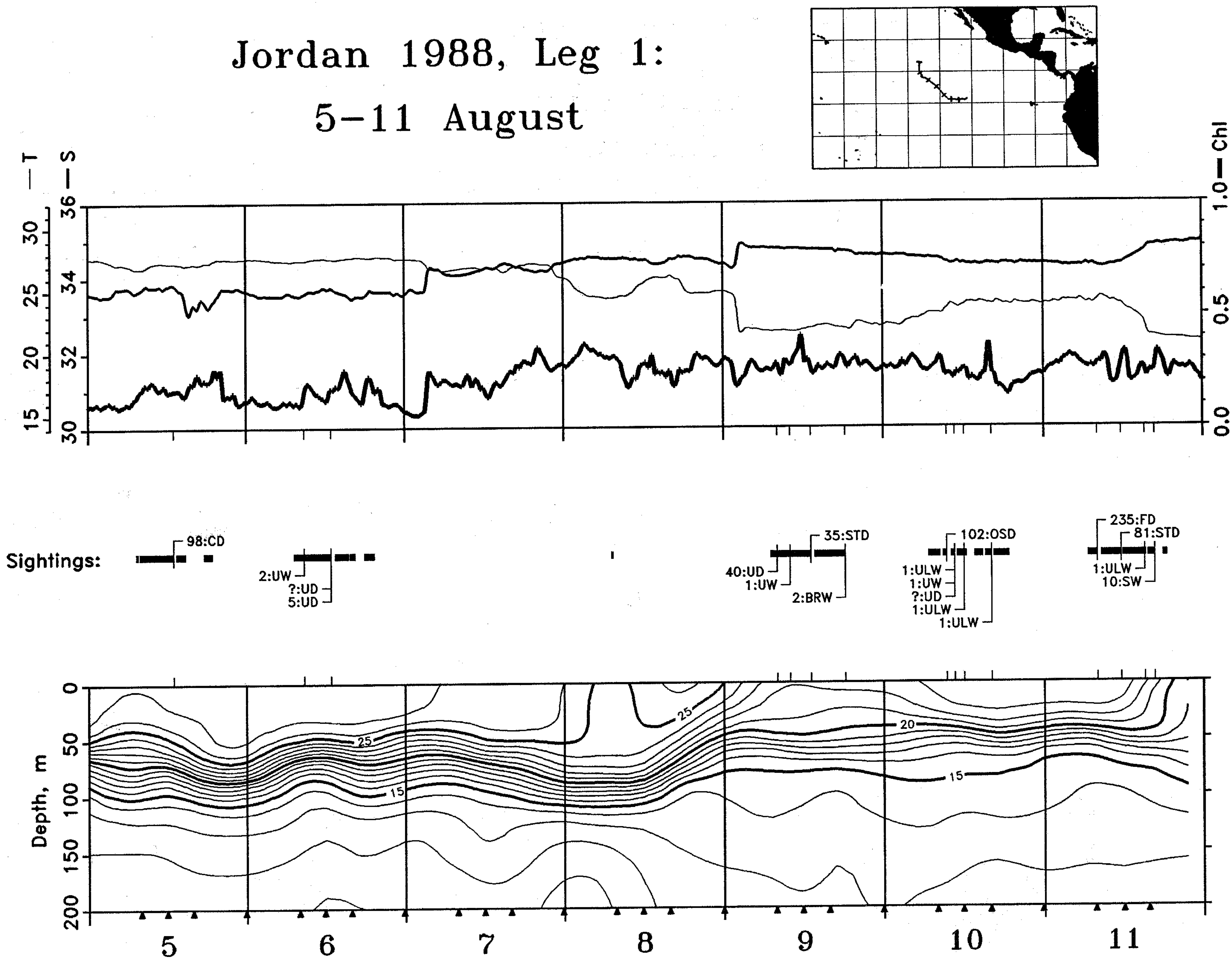
McArthur 1987, Leg 4:
1–7 December



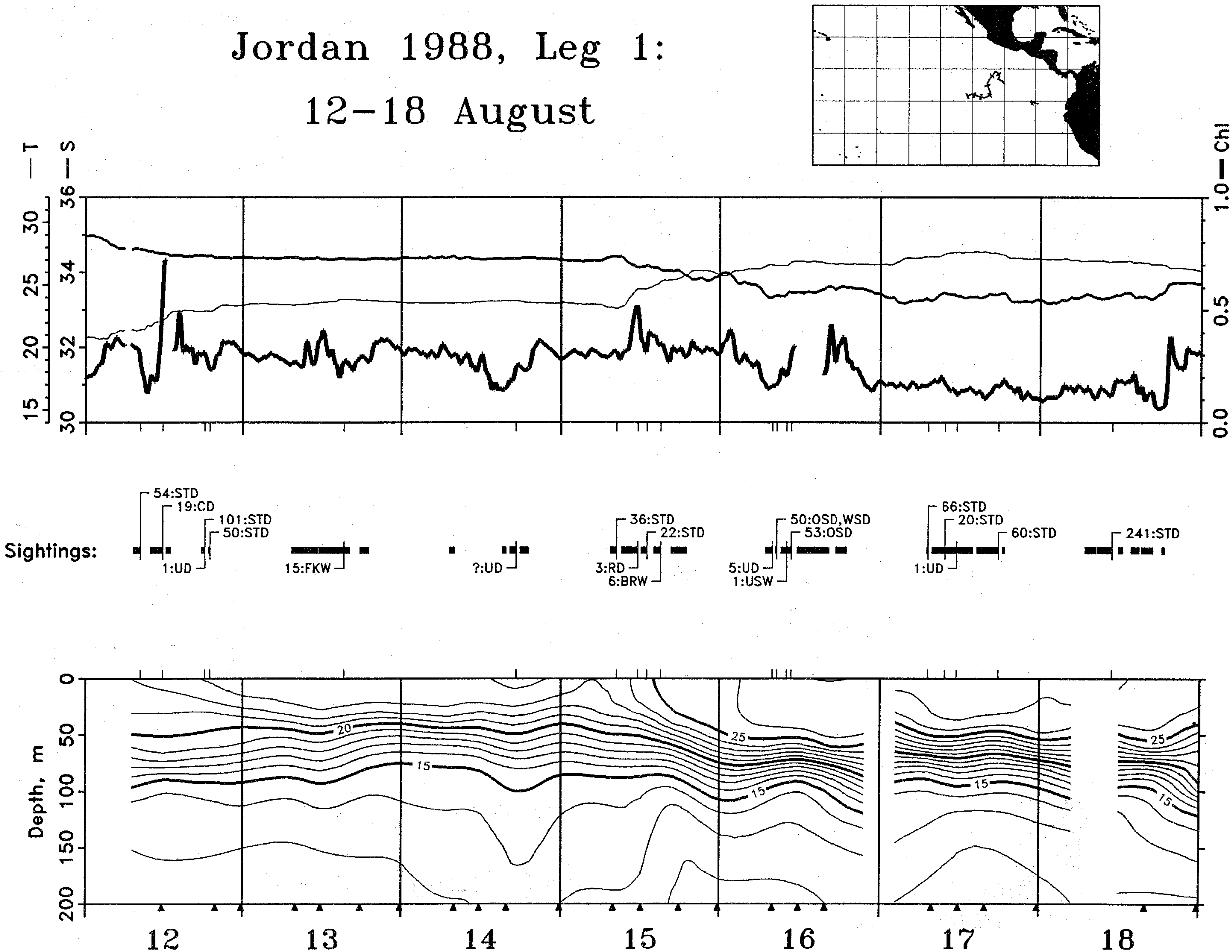




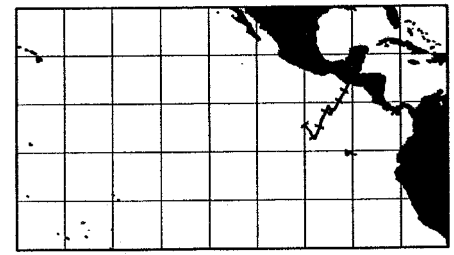
Jordan 1988, Leg 1:
29 July – 4 August
T
S
Chl
1.0
0.5
0.0
36
34
32
30
30
25
20
15
Sightings:
3:UD
19:STD
4:UD
92:STD
71:STD
?:UC
48:WSD
62:WSD,OSD
4:UD
6:UD
1:ULW
436:WSD,OSD
71:OSD
221:WSD,OSD
5:SW
24:UD
26:WSD
100:OSD,WSD
50:OSD
96:STD,WSD,UD
4:UC
Depth, m
0
50
100
150
200
29
30
31
1
2
3
4

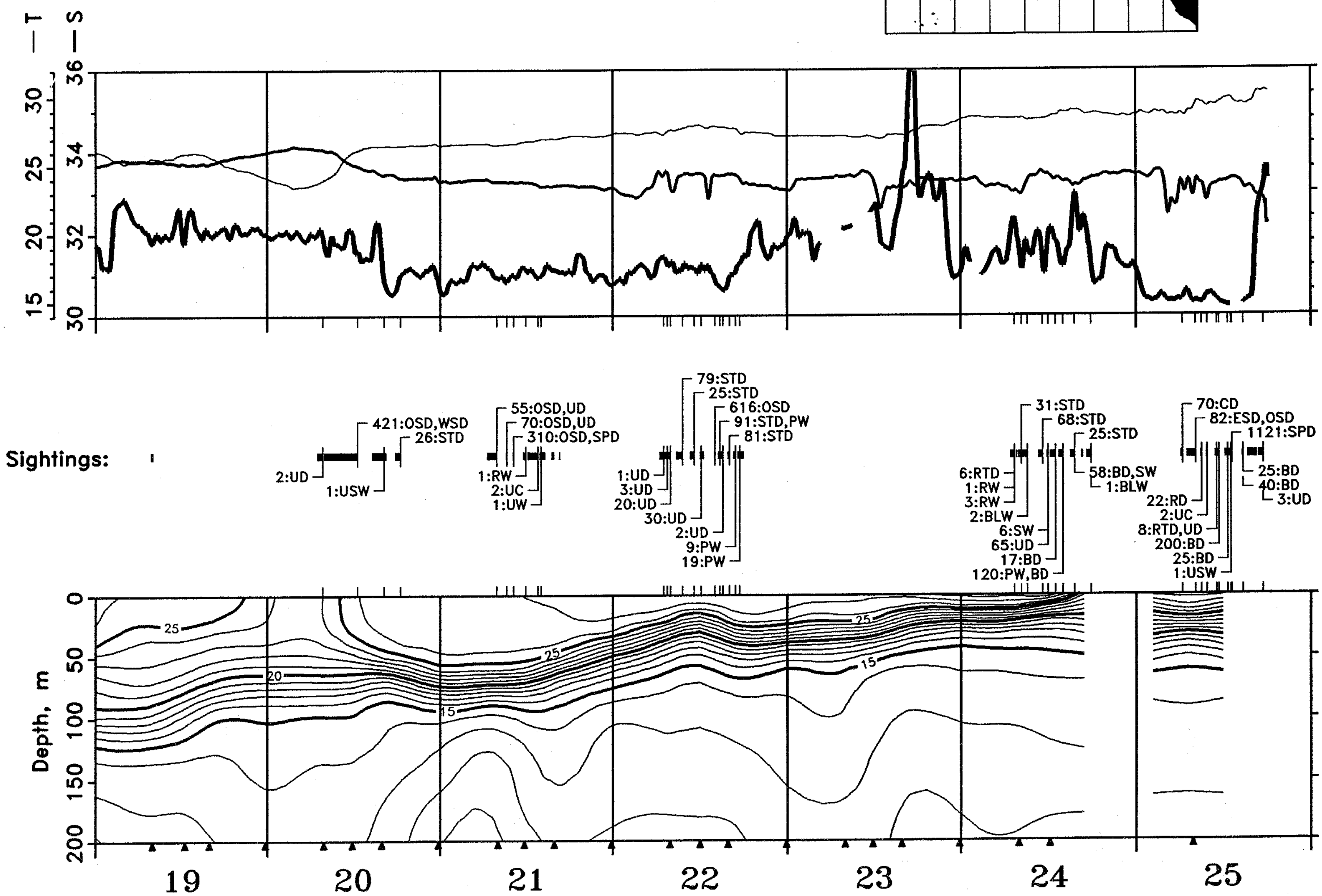

Jordan 1988, Leg 1:
5-11 August
— T
— S
1.0 — Chl
30
25
20
15
36
34
32
30
1.0
0.5
0.0
Sightings:
98:CD
2:UW
?:UD
5:UD
40:UD
1:UW
35:STD
2:BRW
102:OSD
1:ULW
1:UW
?:UD
1:ULW
1:ULW
235:FD
81:STD
1:ULW
10:SW
Depth, m
0
50
100
150
200
25
15
25
20
15
5
6
7
8
9
10
11

Jordan 1988, Leg 1:
12–18 August

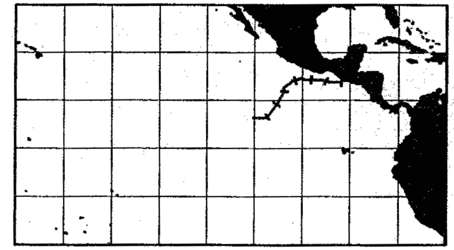


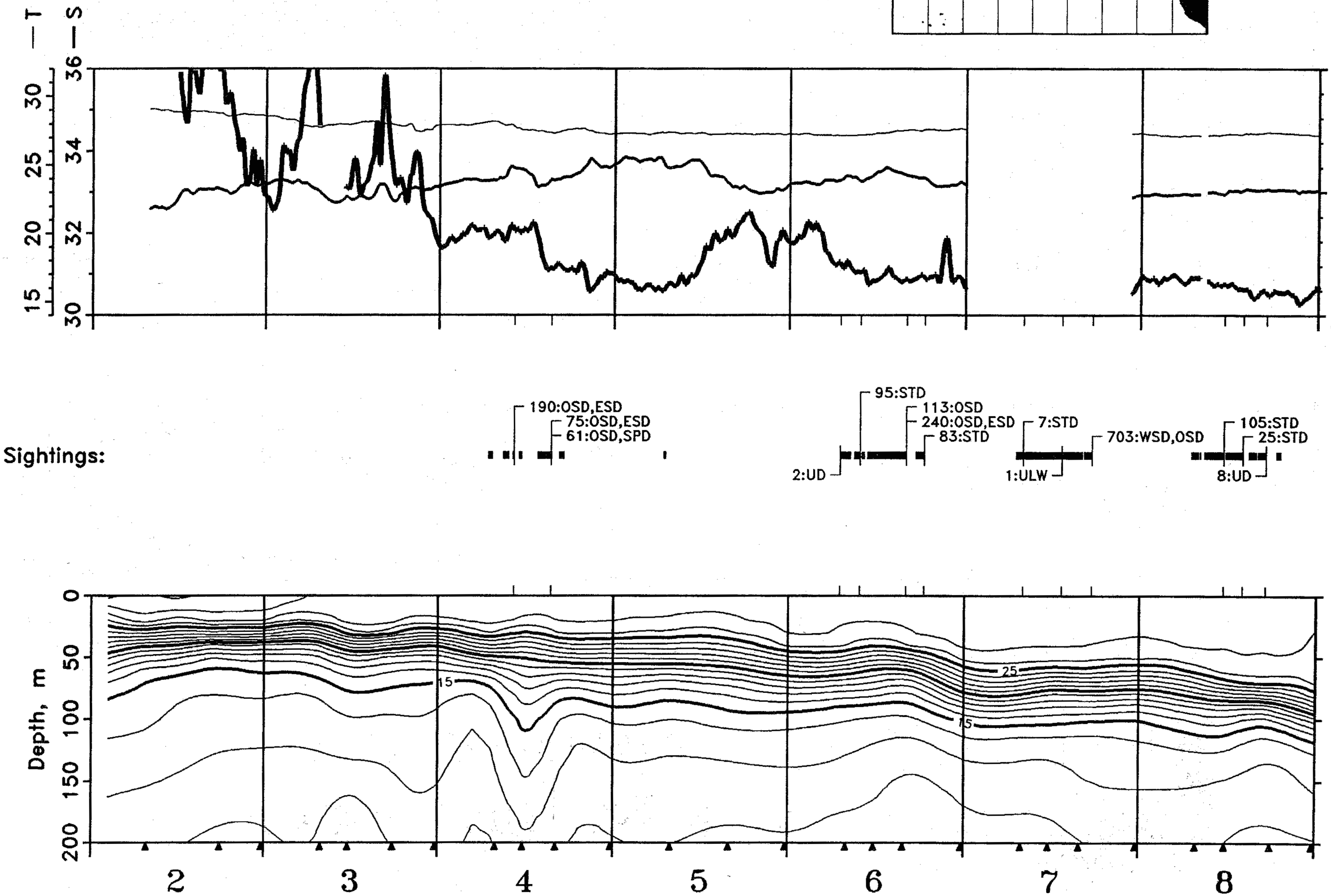
Jordan 1988, Leg 1:
19–25 August



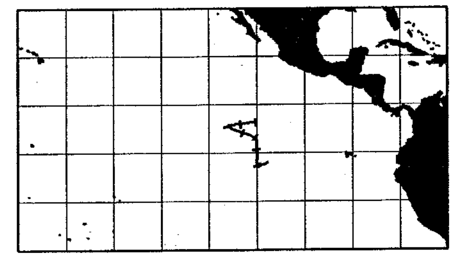


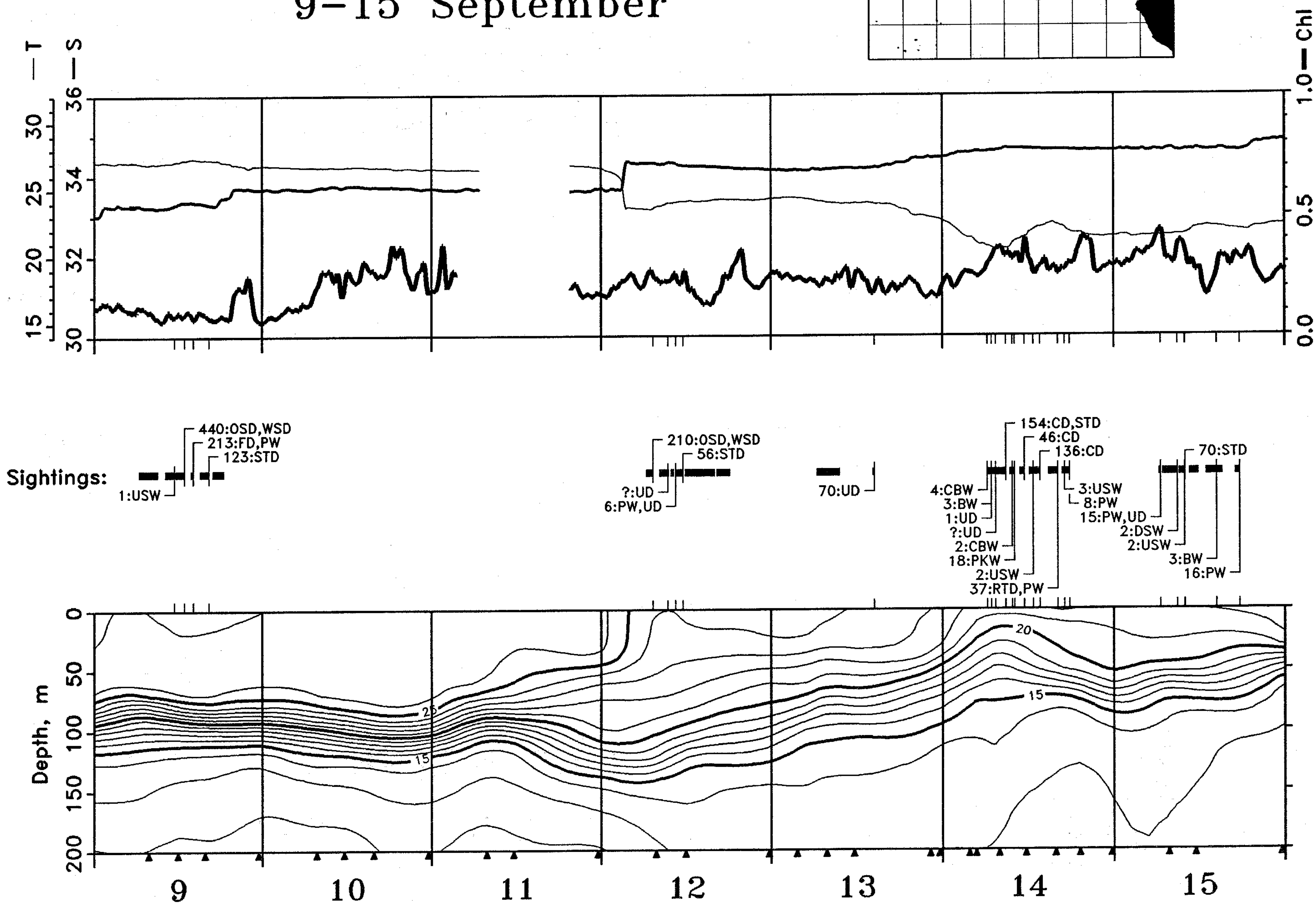
Jordan 1988, Leg 2:
2–8 September



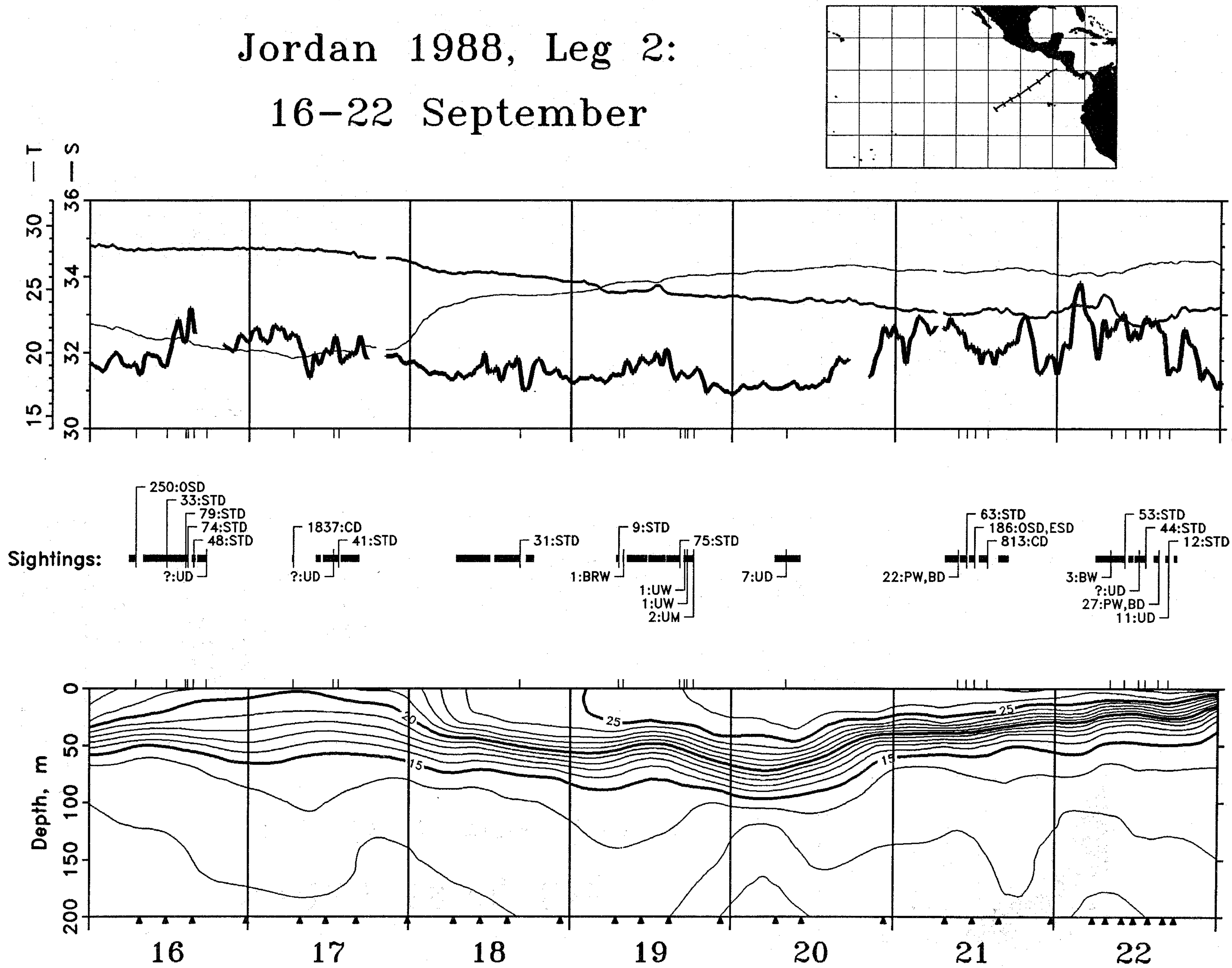


Jordan 1988, Leg 2:
9–15 September

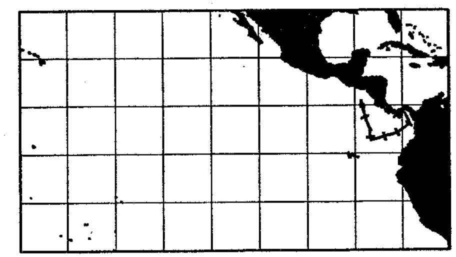


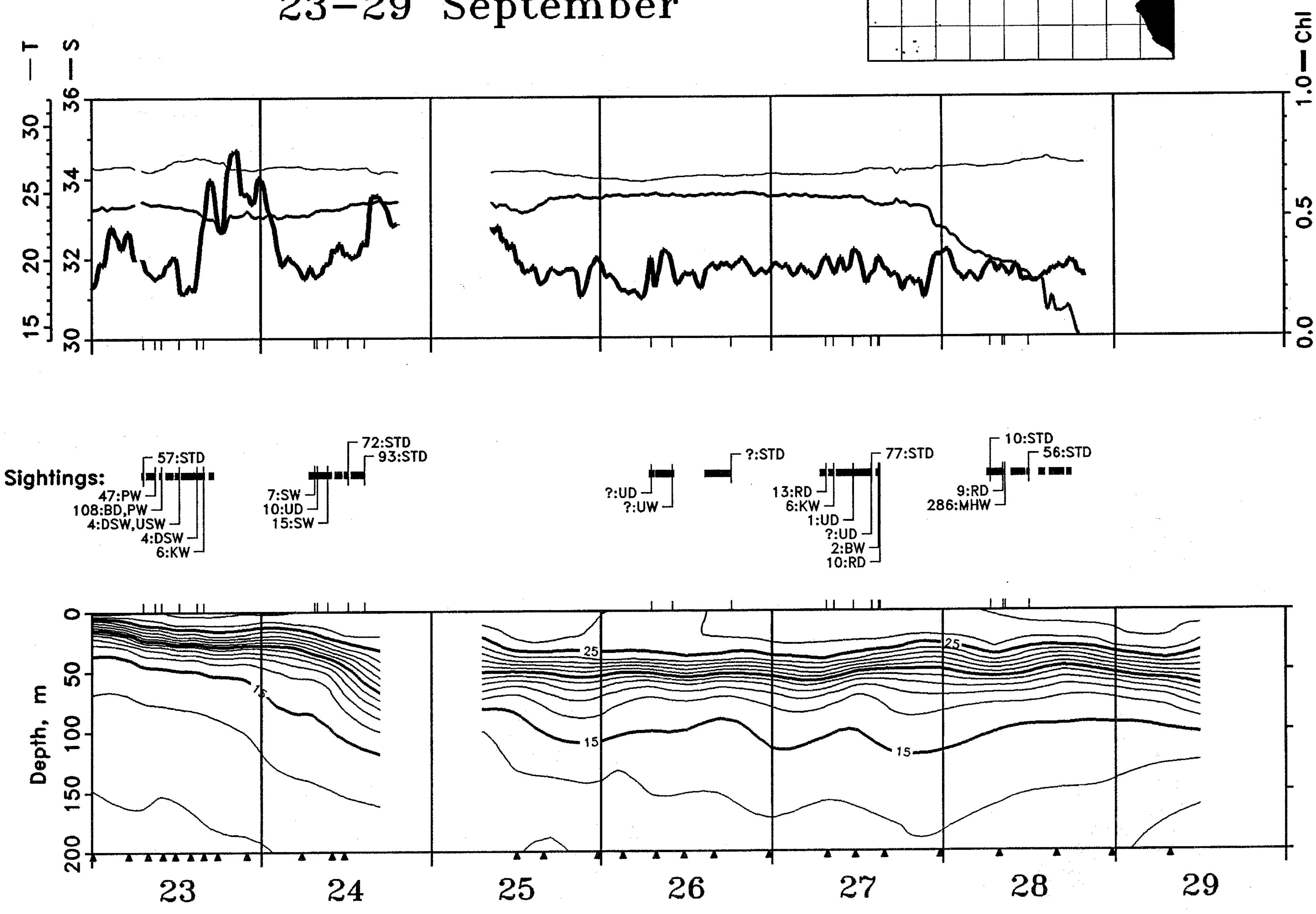


Jordan 1988, Leg 2:
16–22 September

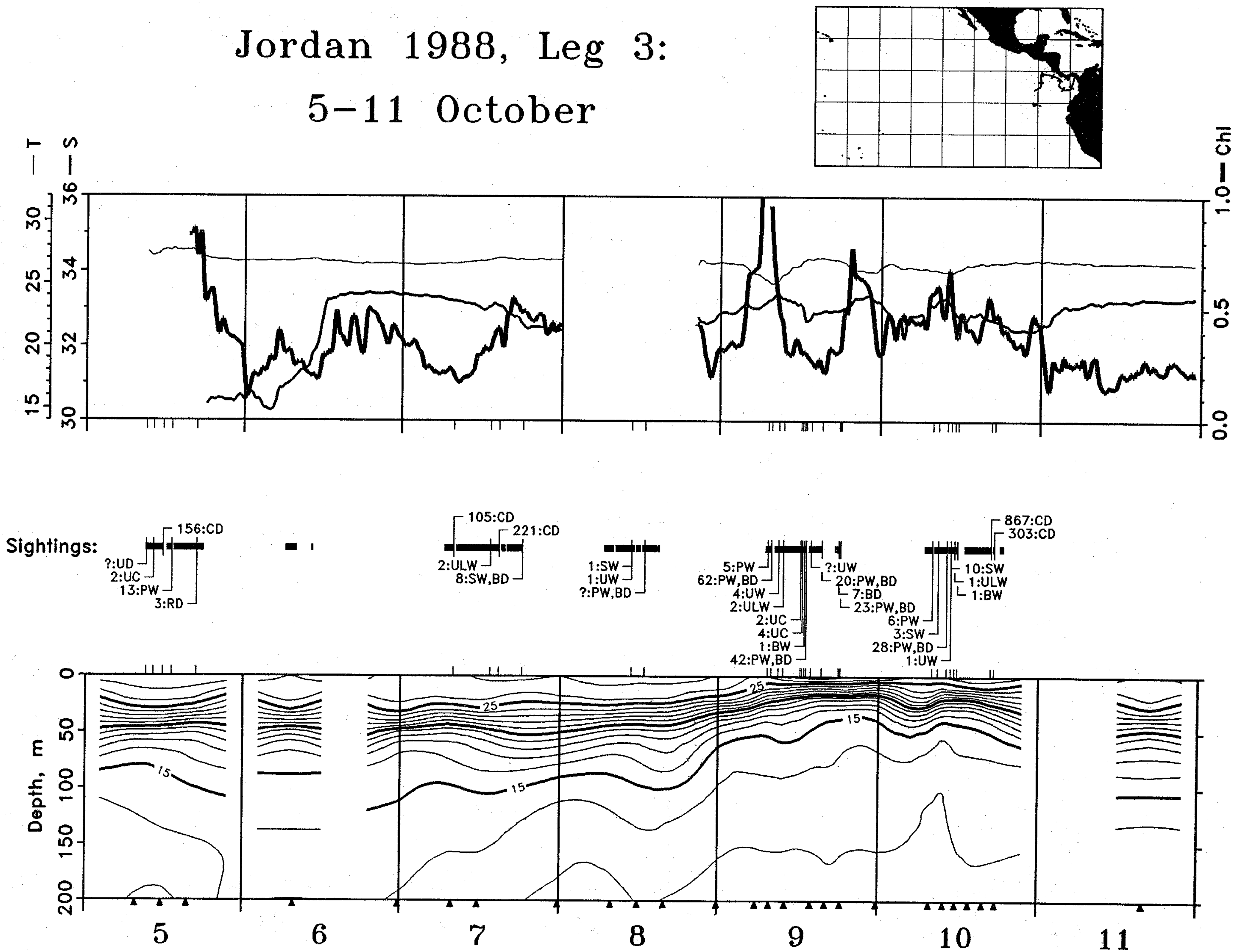


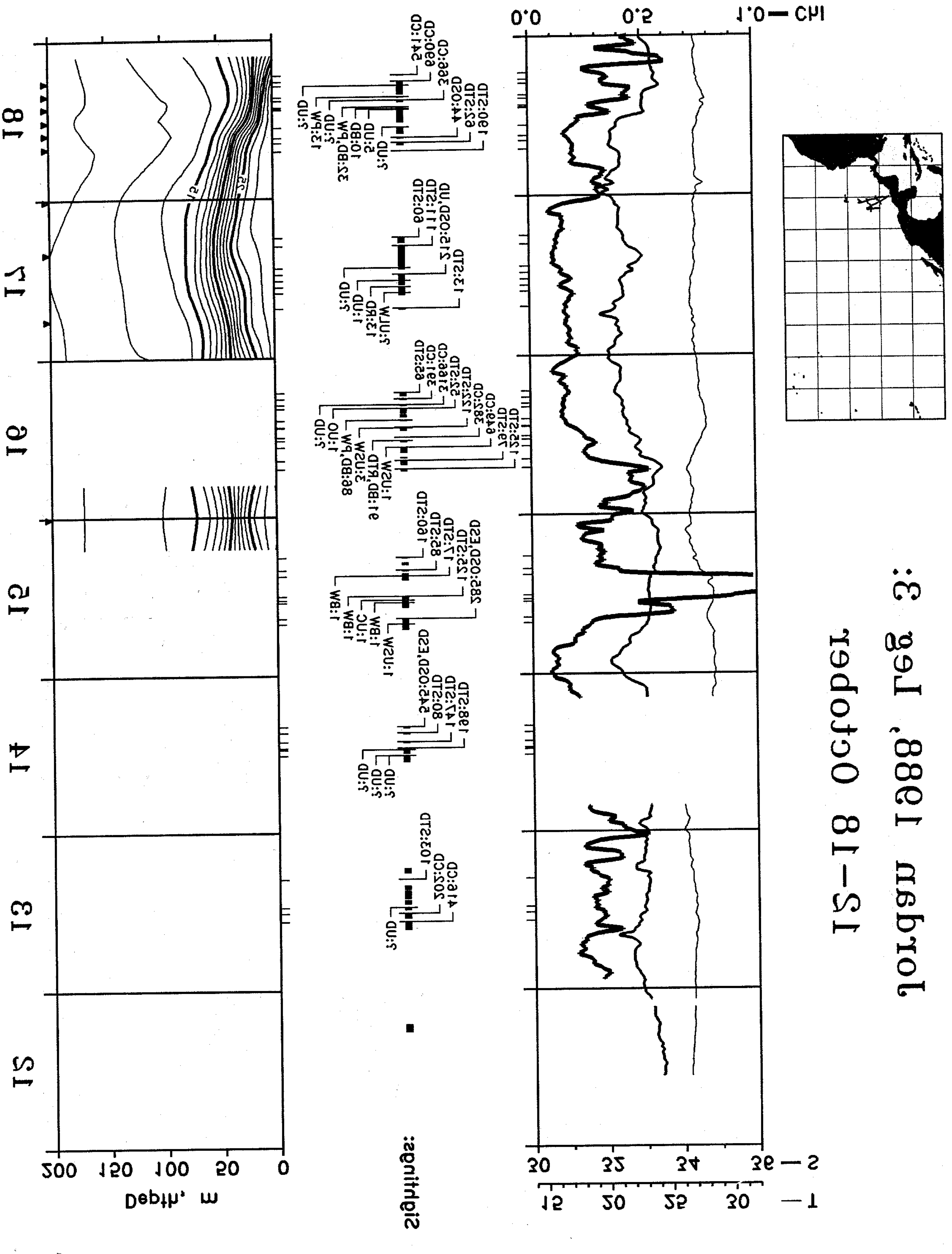
Jordan 1988, Leg 2:
23–29 September



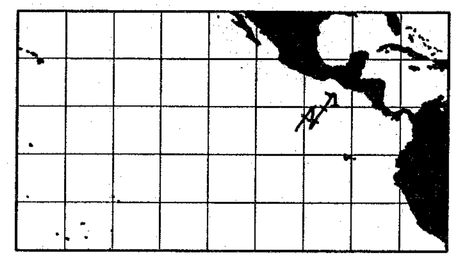


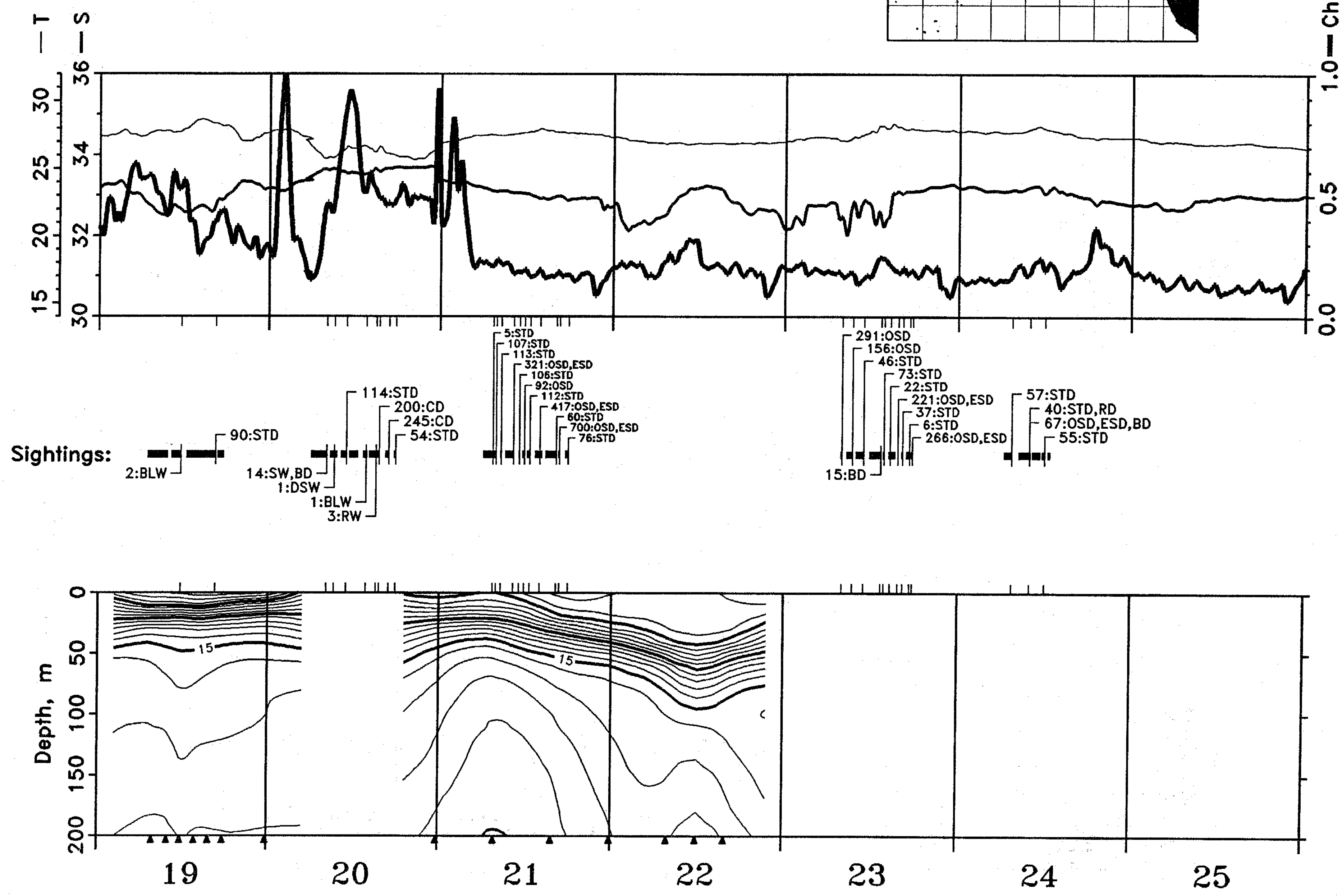
Jordan 1988, Leg 3:
5–11 October



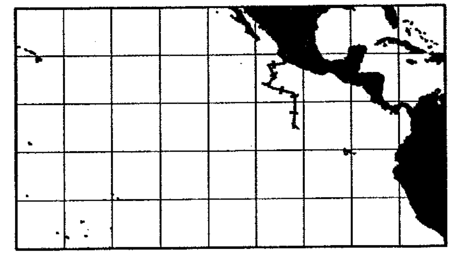

Jordan 1988, Leg 3:
12-18 October
Depth, m
Sightings:
S
T
Chl
12
13
14
15
16
17
18

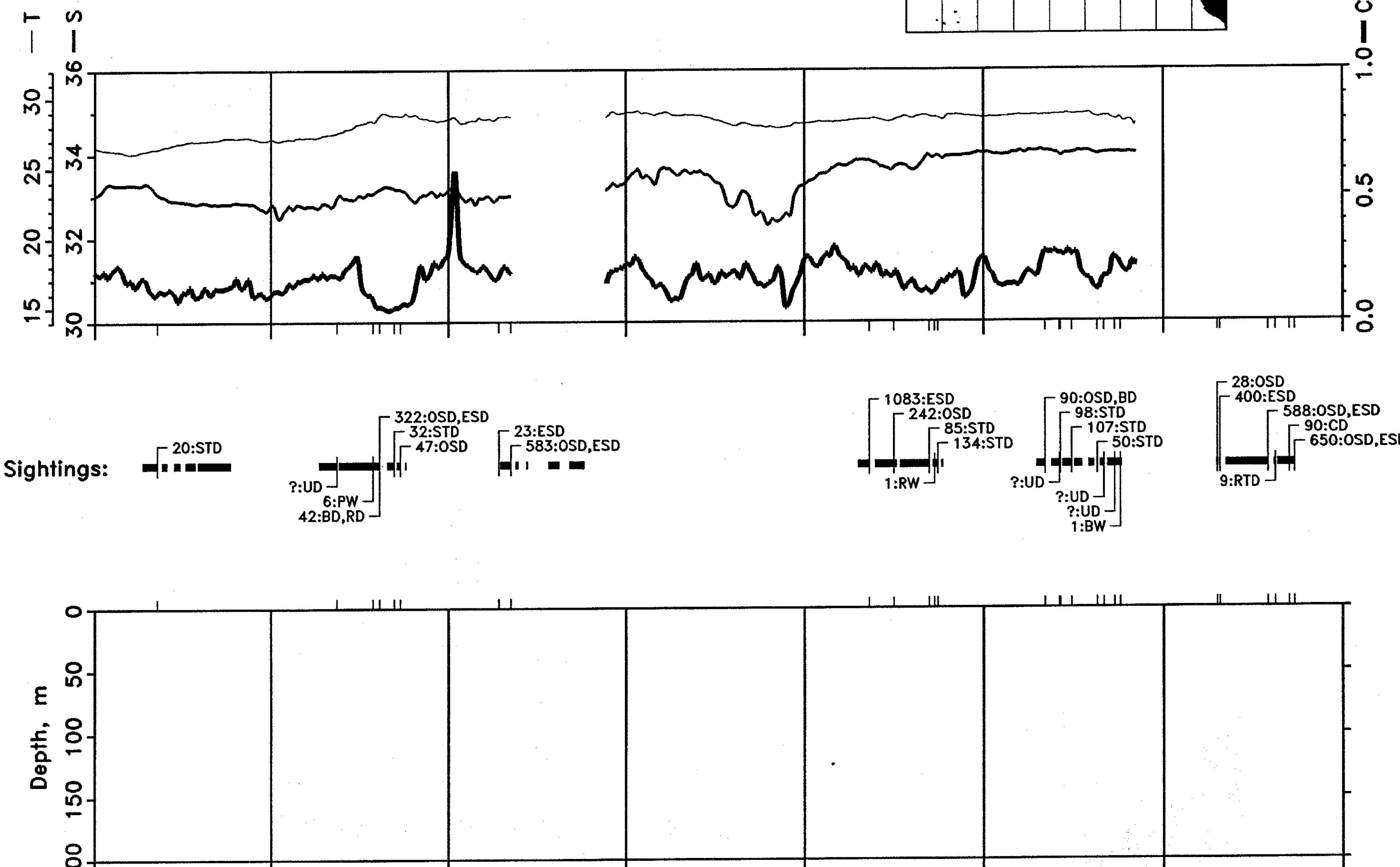
Jordan 1988, Leg 3:
19–25 October



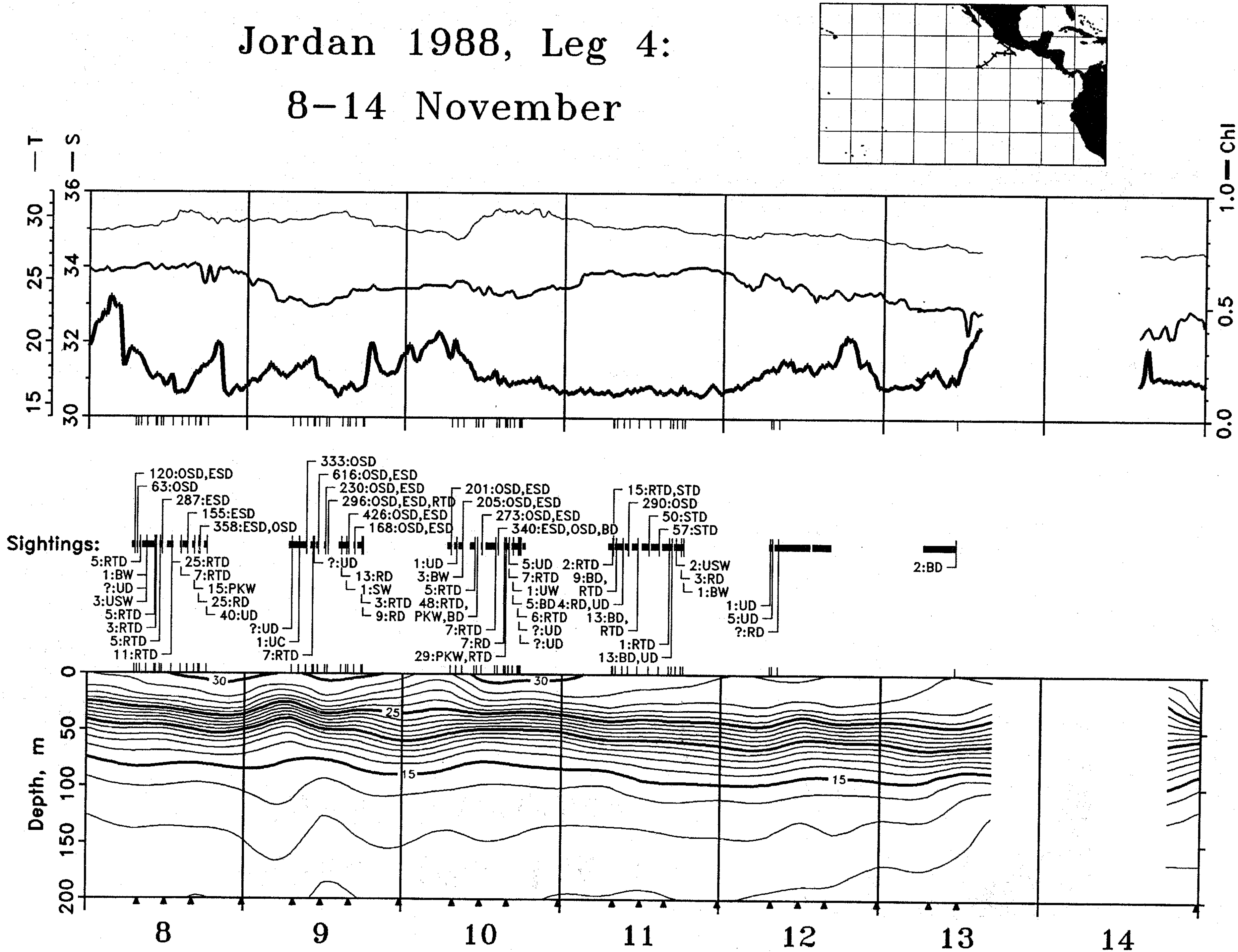


Jordan 1988, Leg 3:
26 October – 1 November

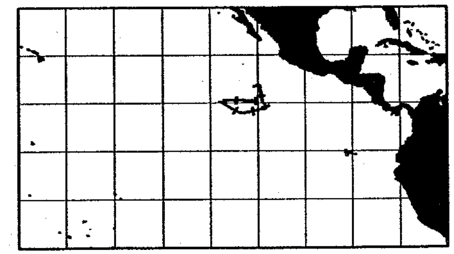


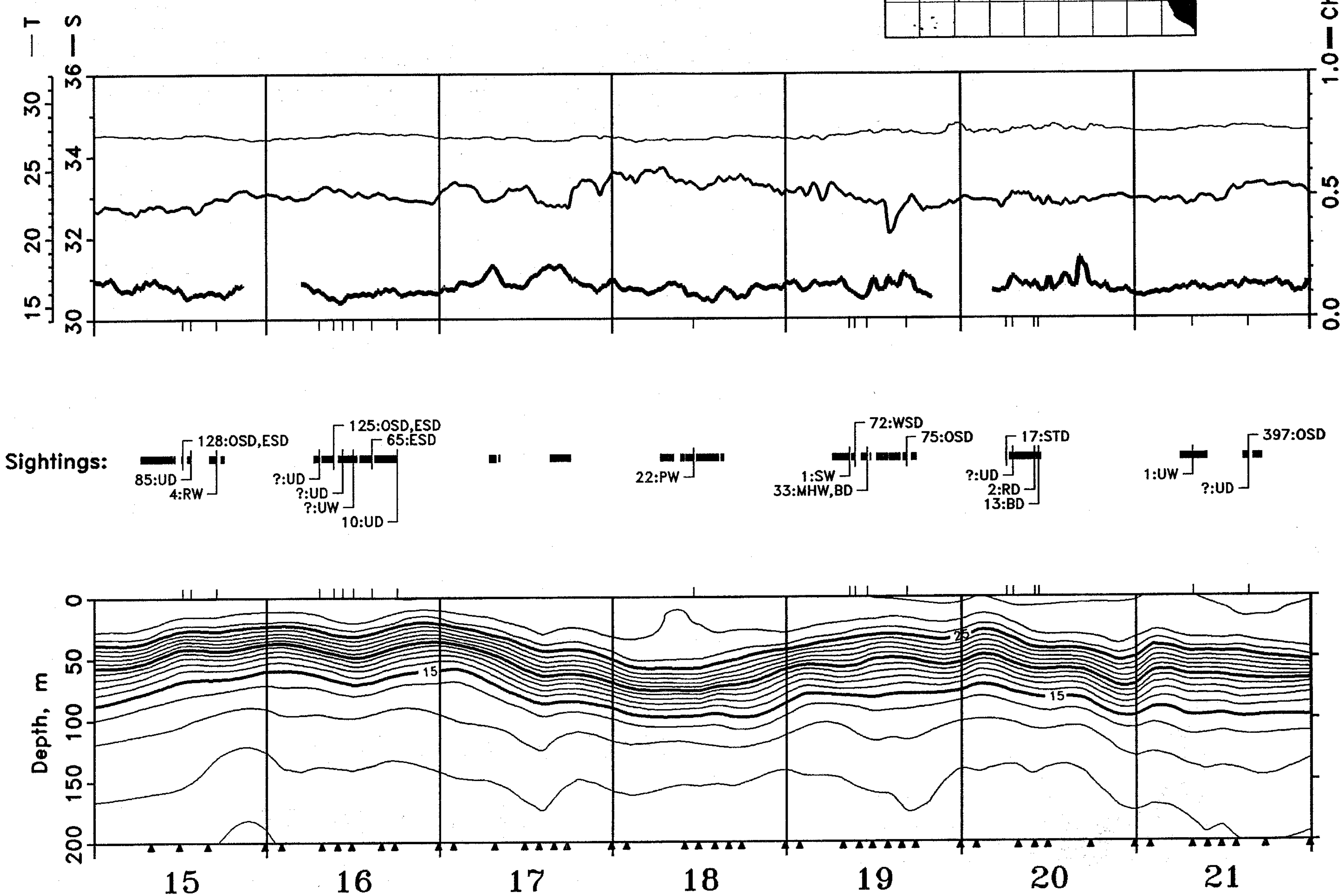


Jordan 1988, Leg 4:
8–14 November

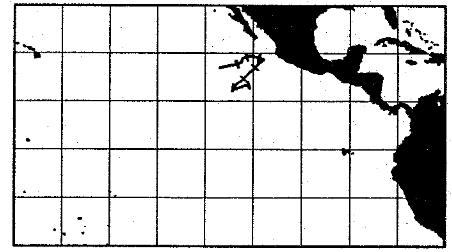


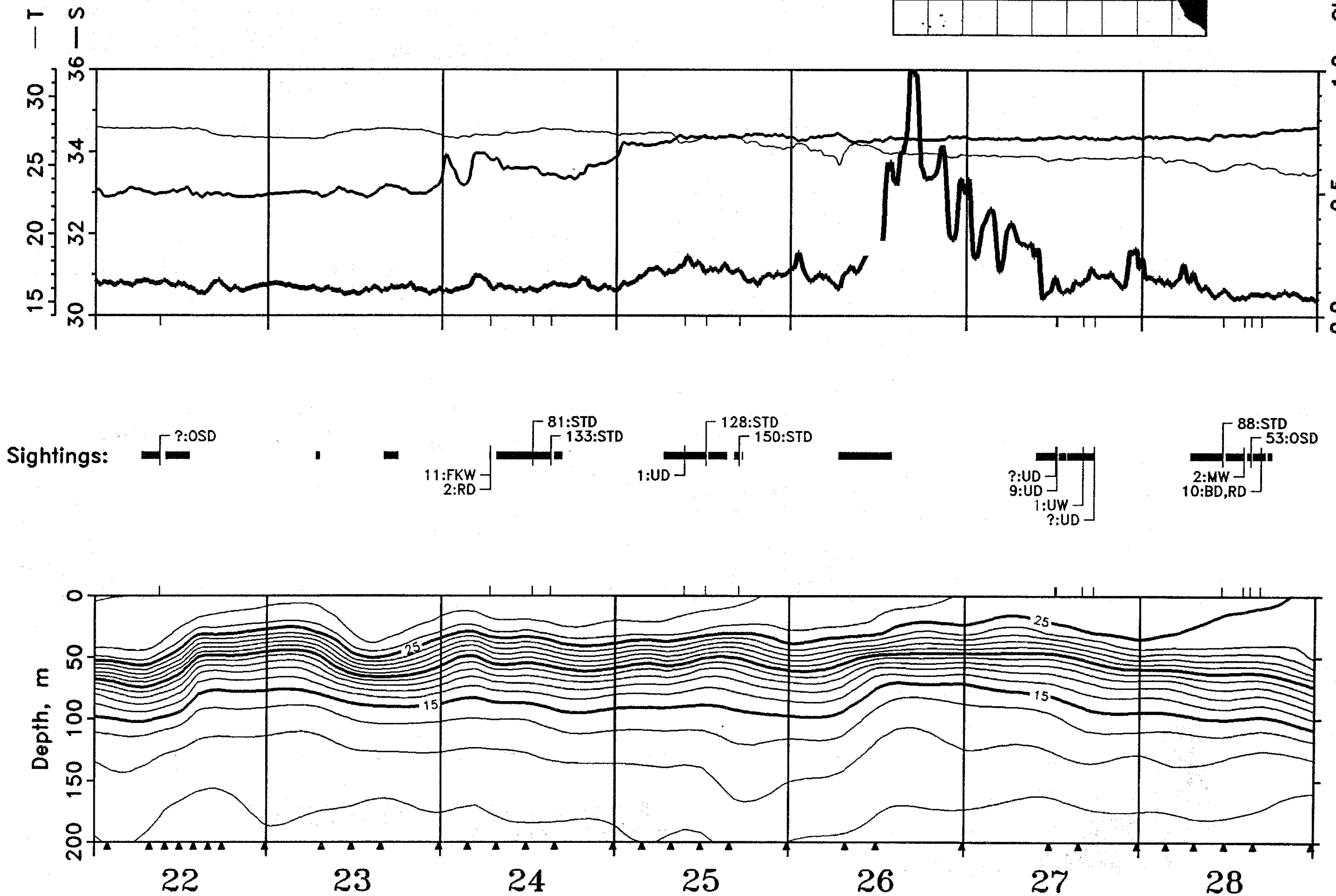
Jordan 1988, Leg 4: 15–21 November



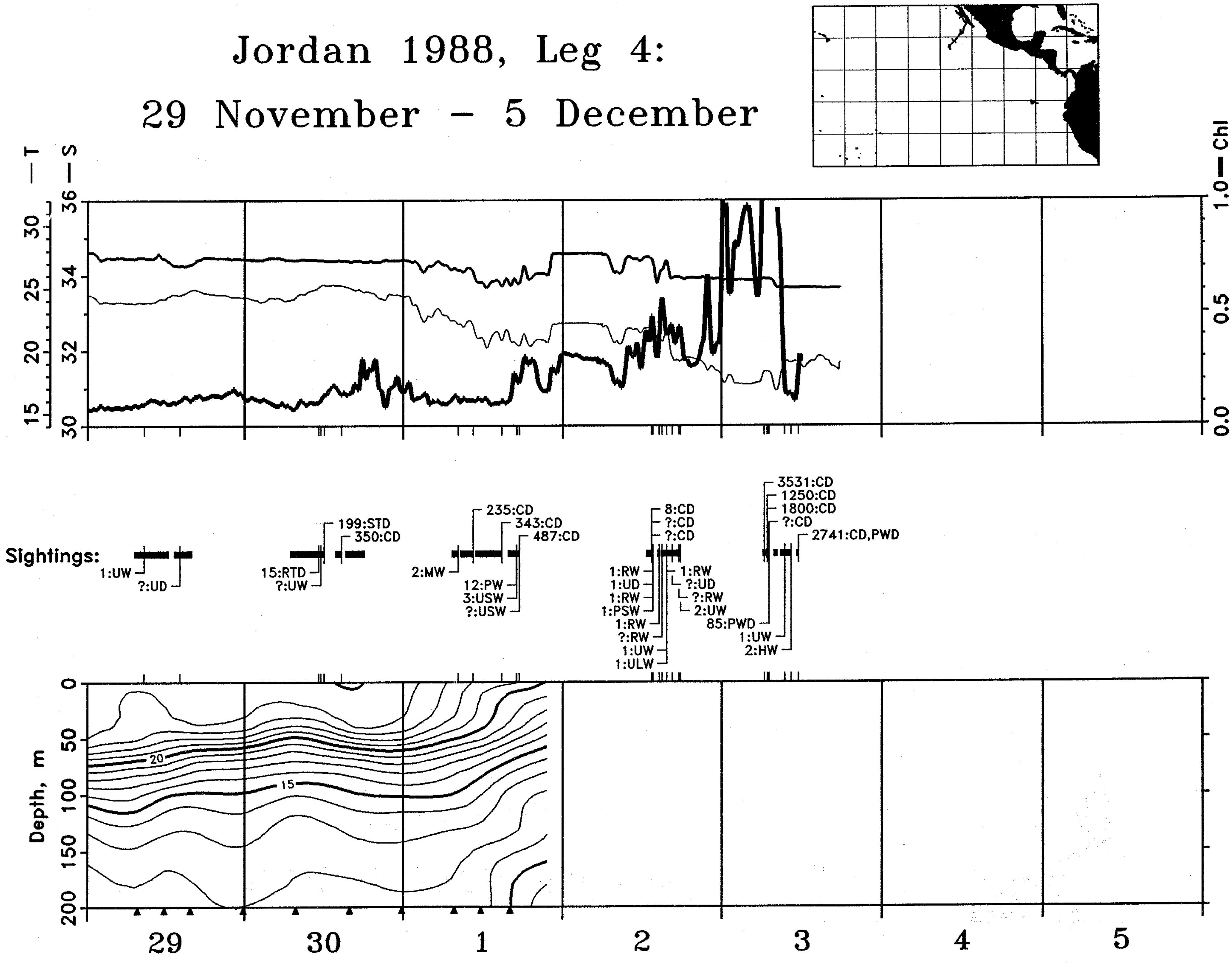


Jordan 1988, Leg 4:
22–28 November

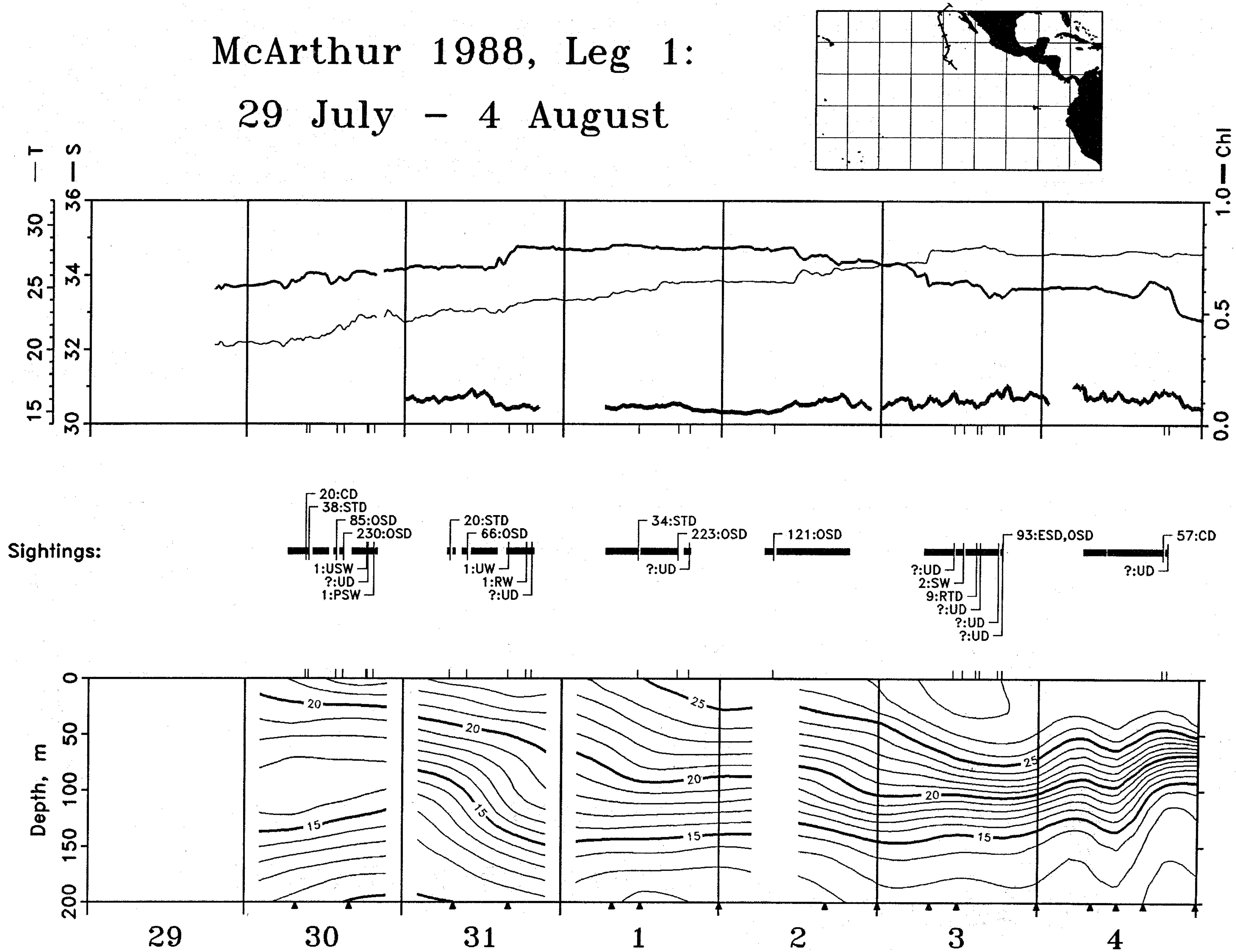




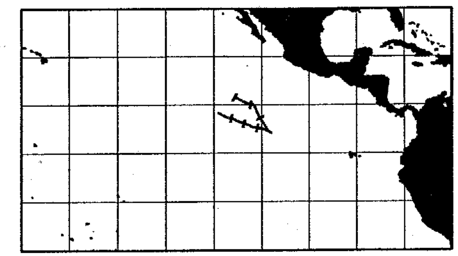
Jordan 1988, Leg 4:
29 November – 5 December

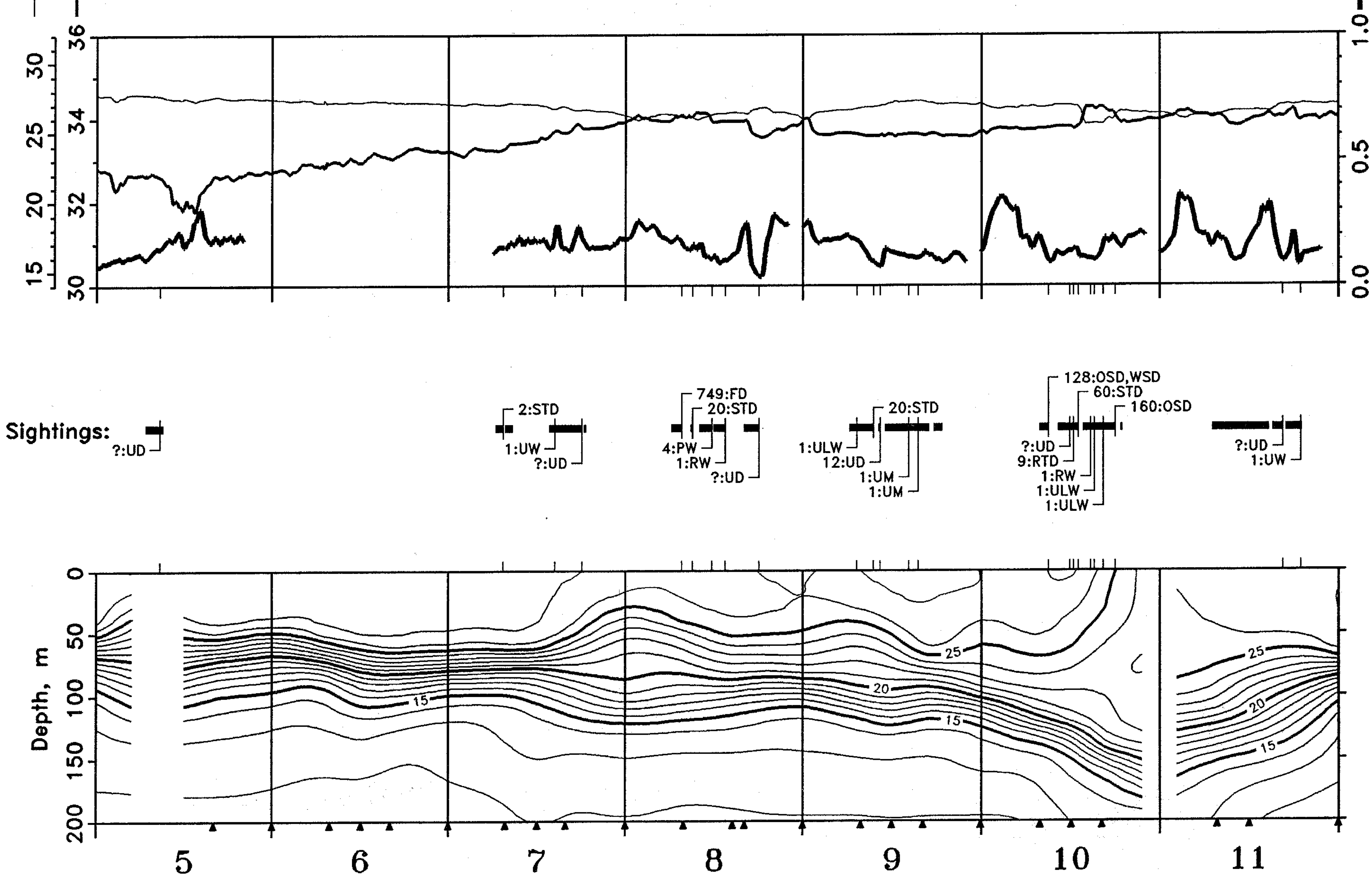


McArthur 1988, Leg 1:
29 July – 4 August

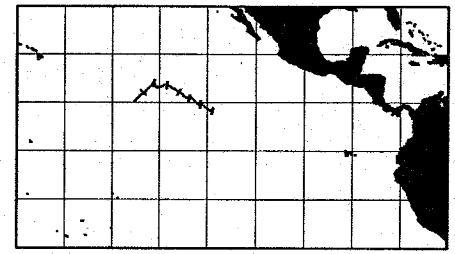


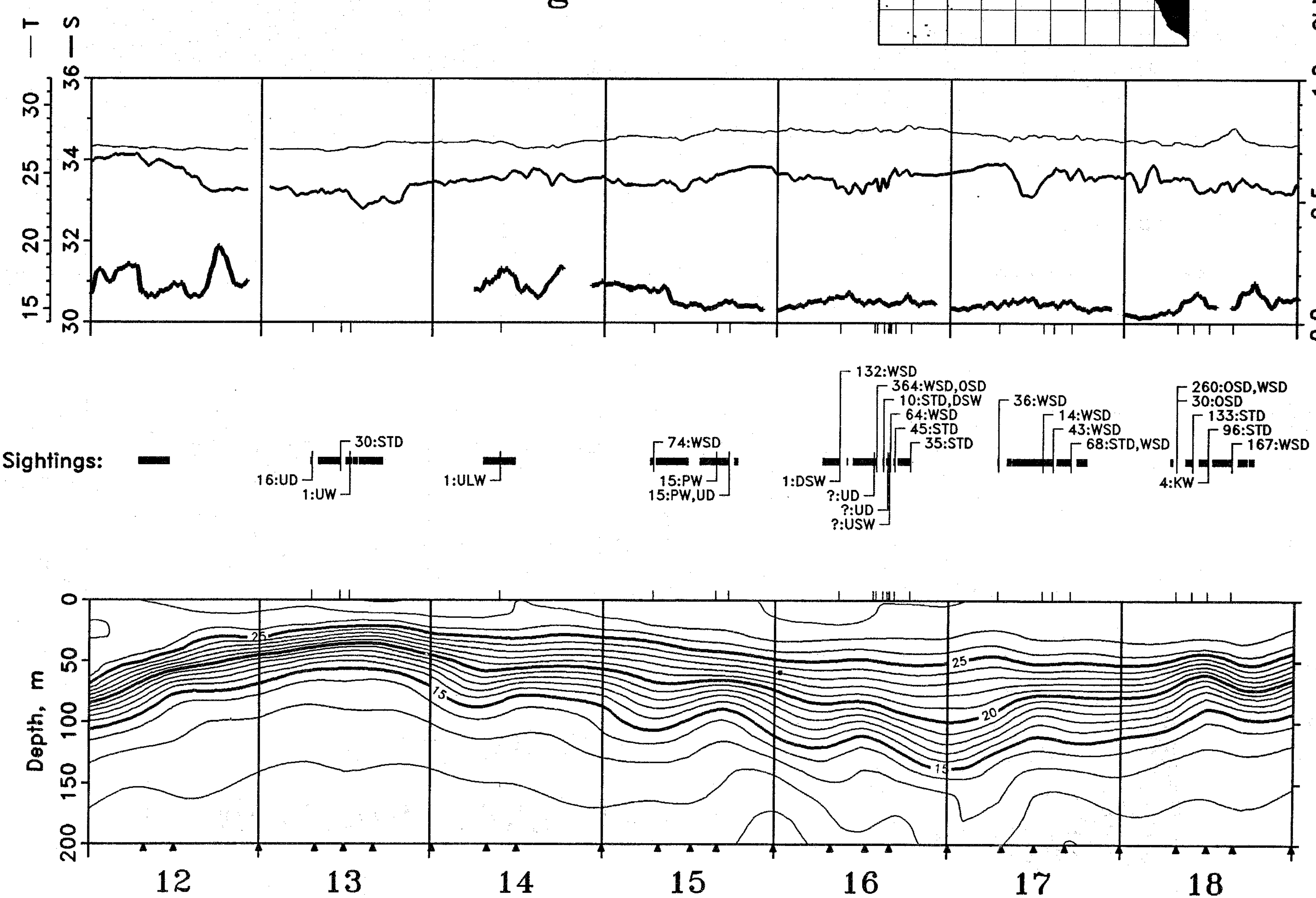
McArthur 1988, Leg 1:
5–11 August

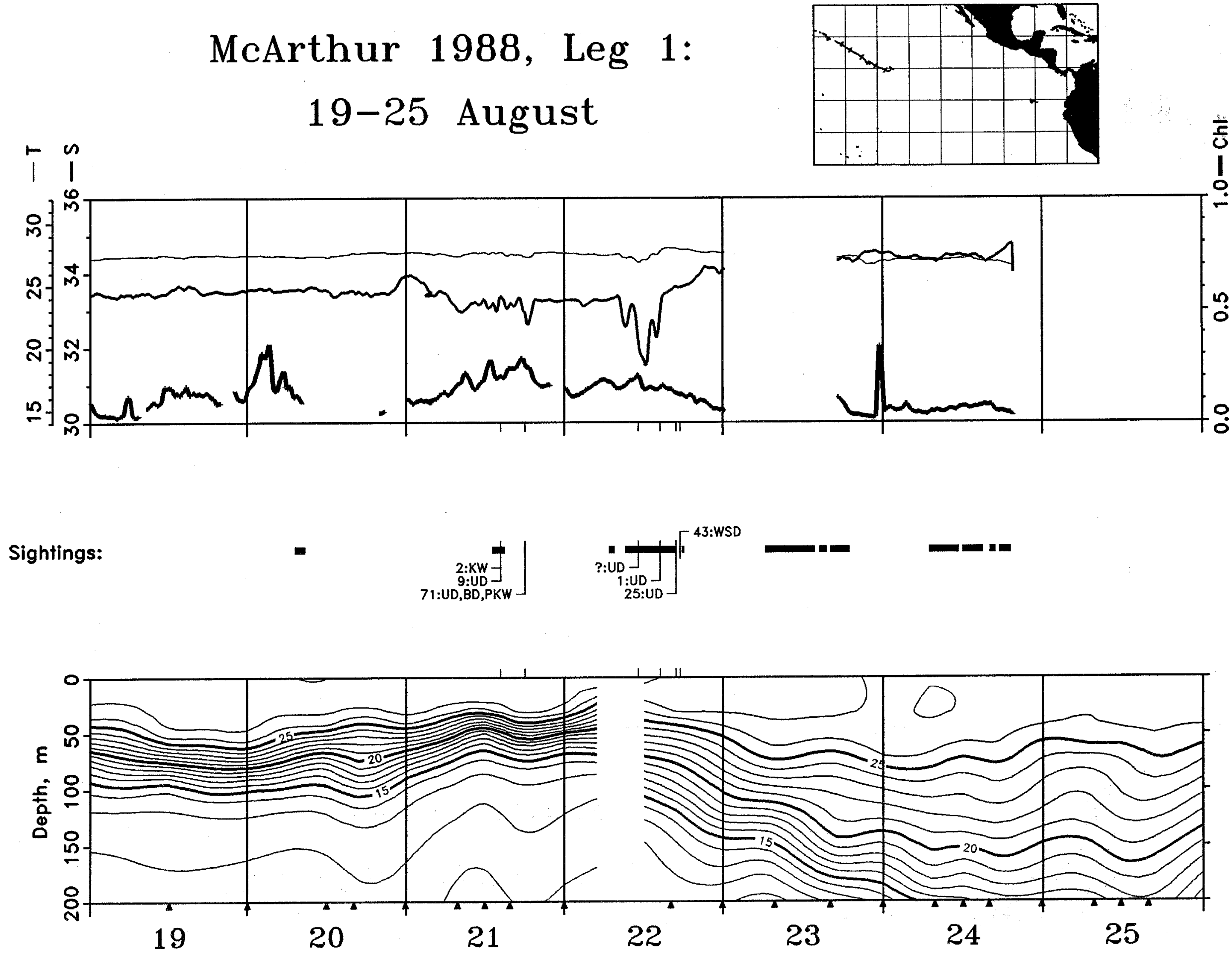




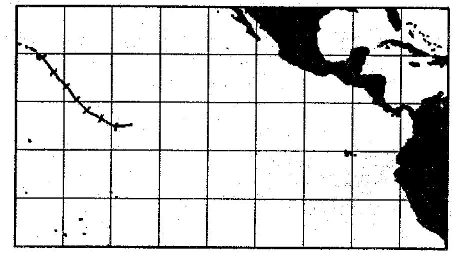
McArthur 1988, Leg 1:
12–18 August

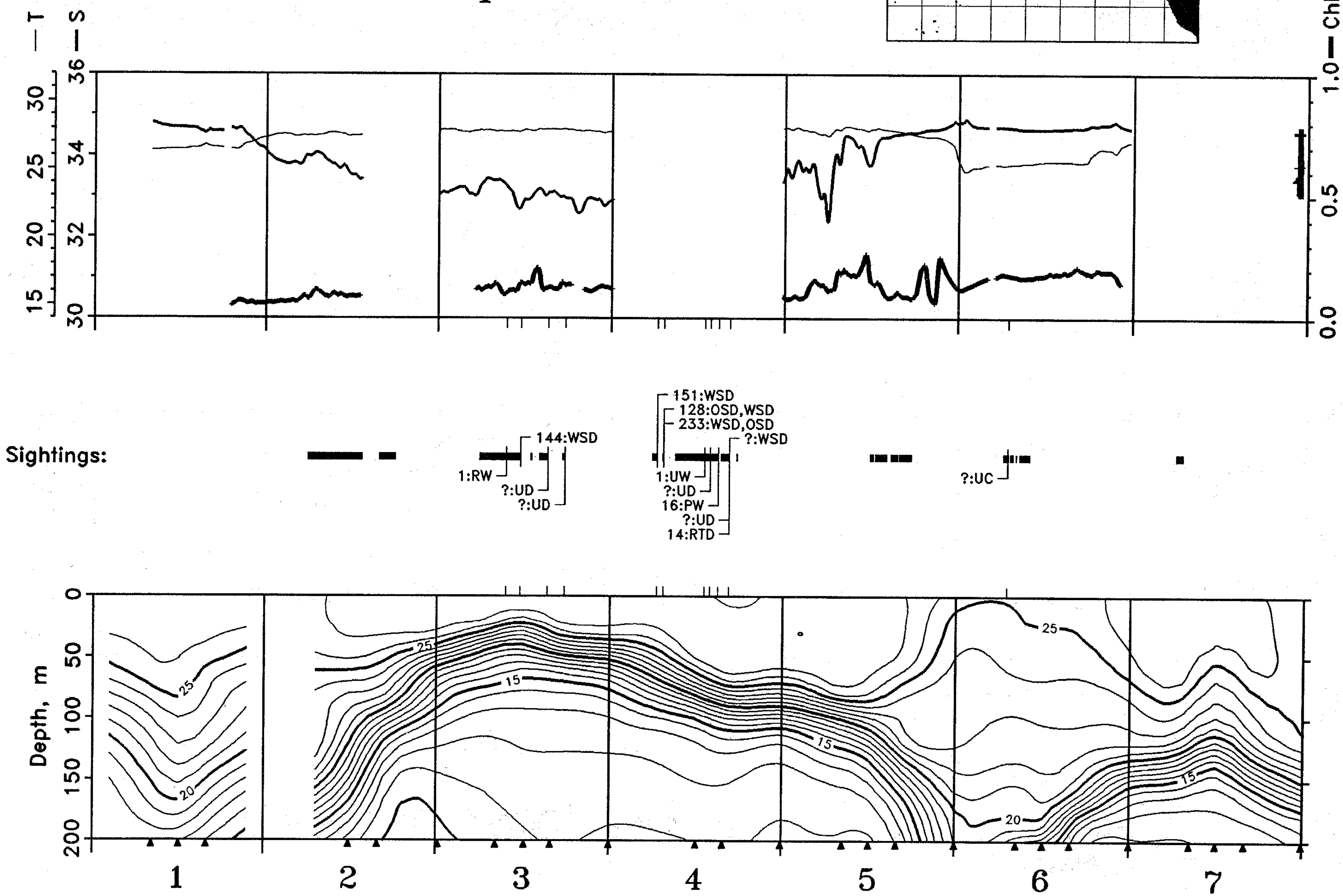




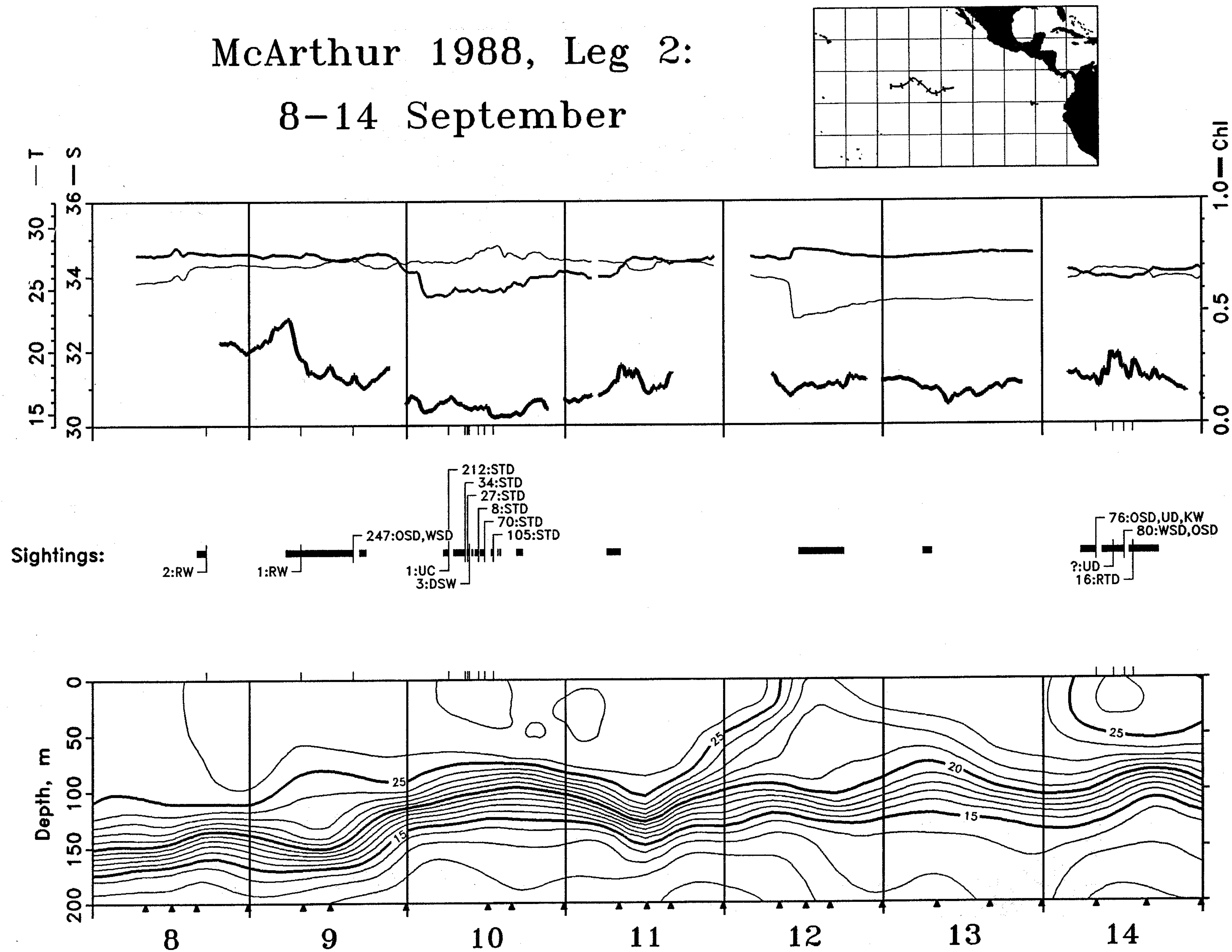

McArthur 1988, Leg 1:
19–25 August
— T
— S
1.0 — Chl
Sightings:
2:KW
9:UD
71:UD,BD,PKW
?:UD
1:UD
25:UD
43:WSD
Depth, m
19
20
21
22
23
24
25

McArthur 1988, Leg 2:
1–7 September

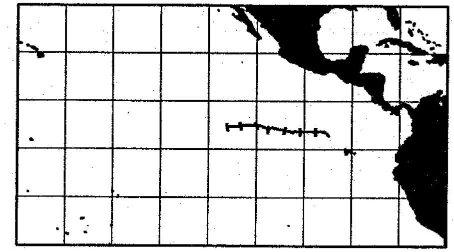


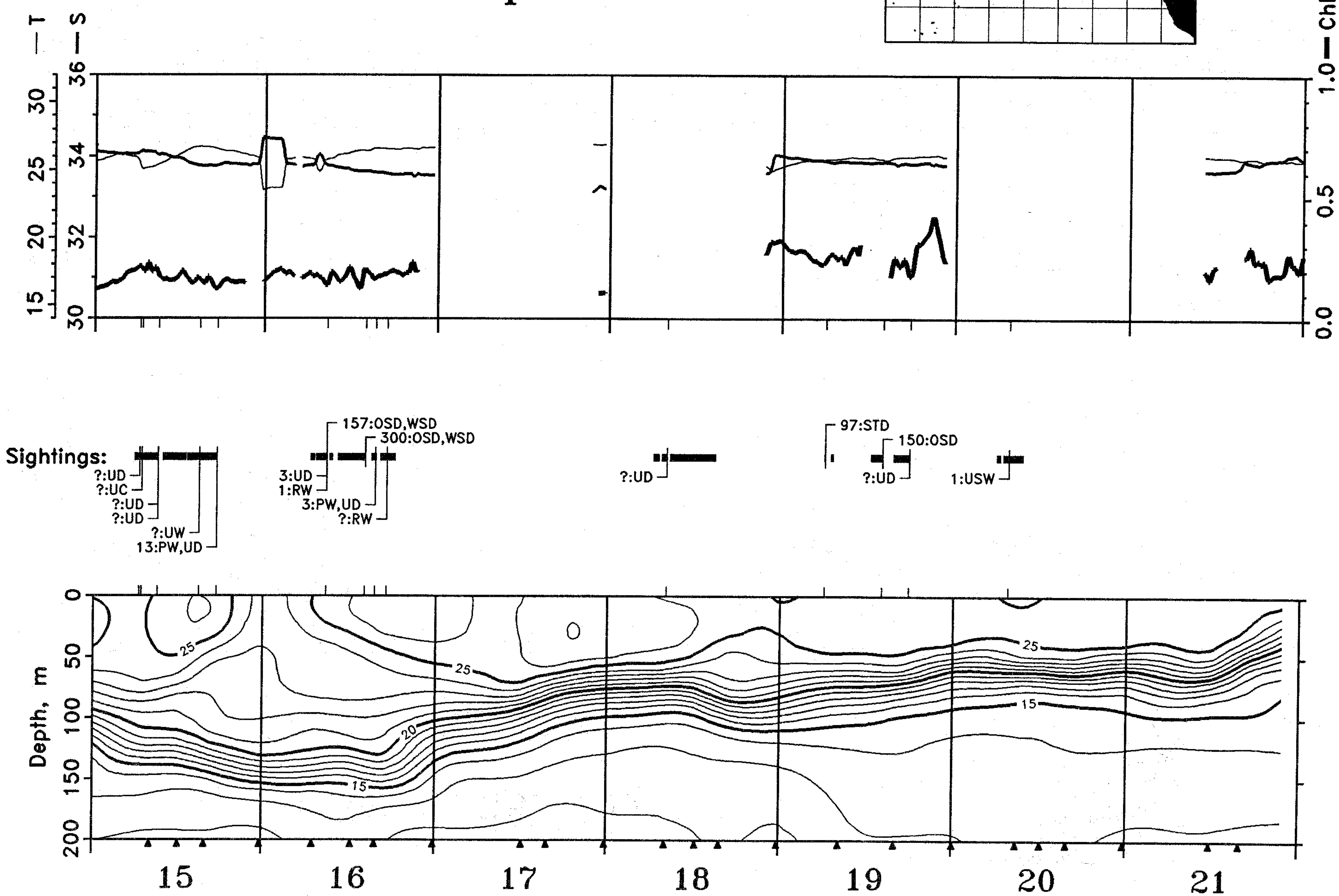


McArthur 1988, Leg 2: 8–14 September

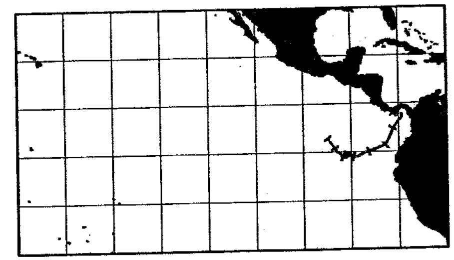


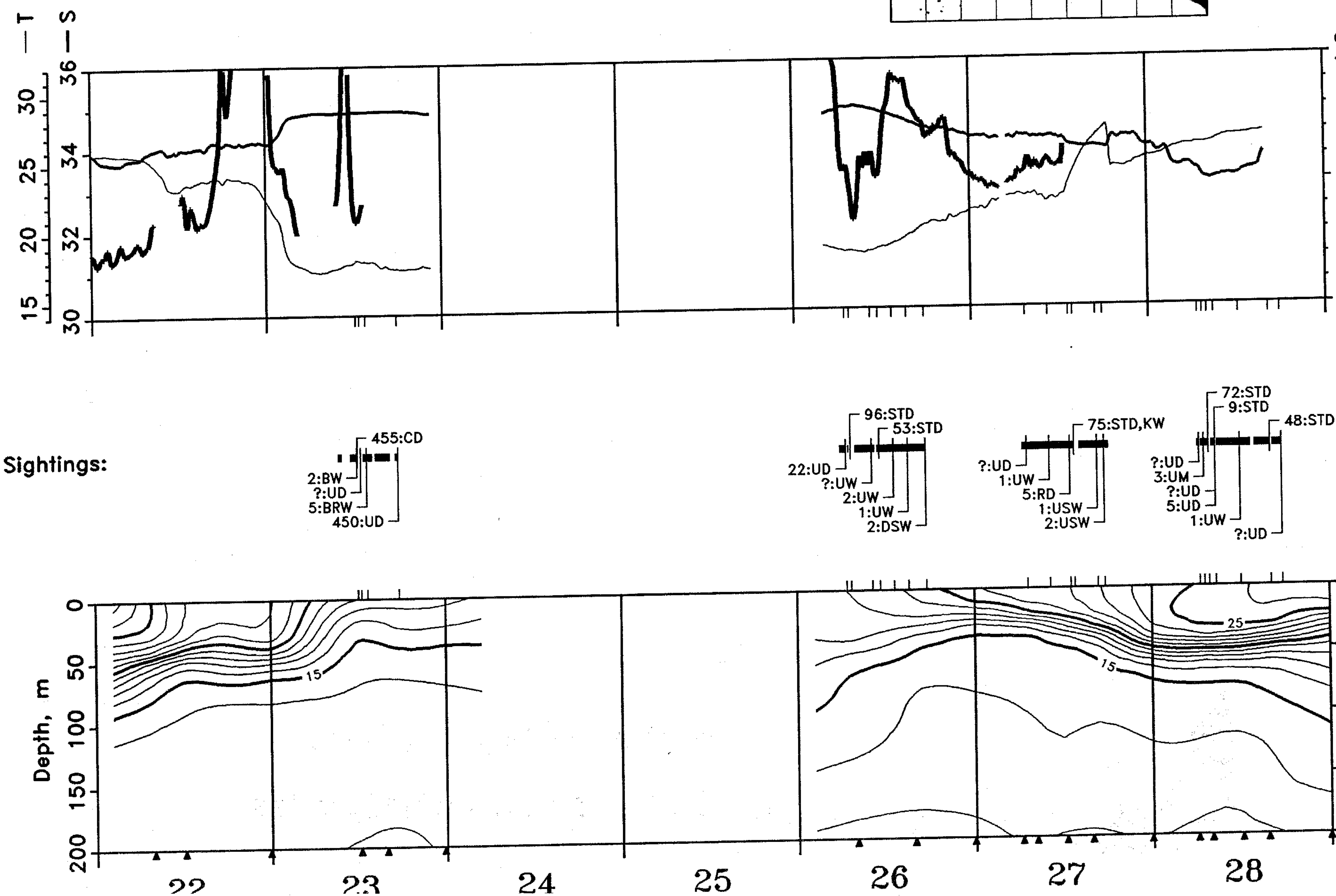
McArthur 1988, Leg 2:
15–21 September

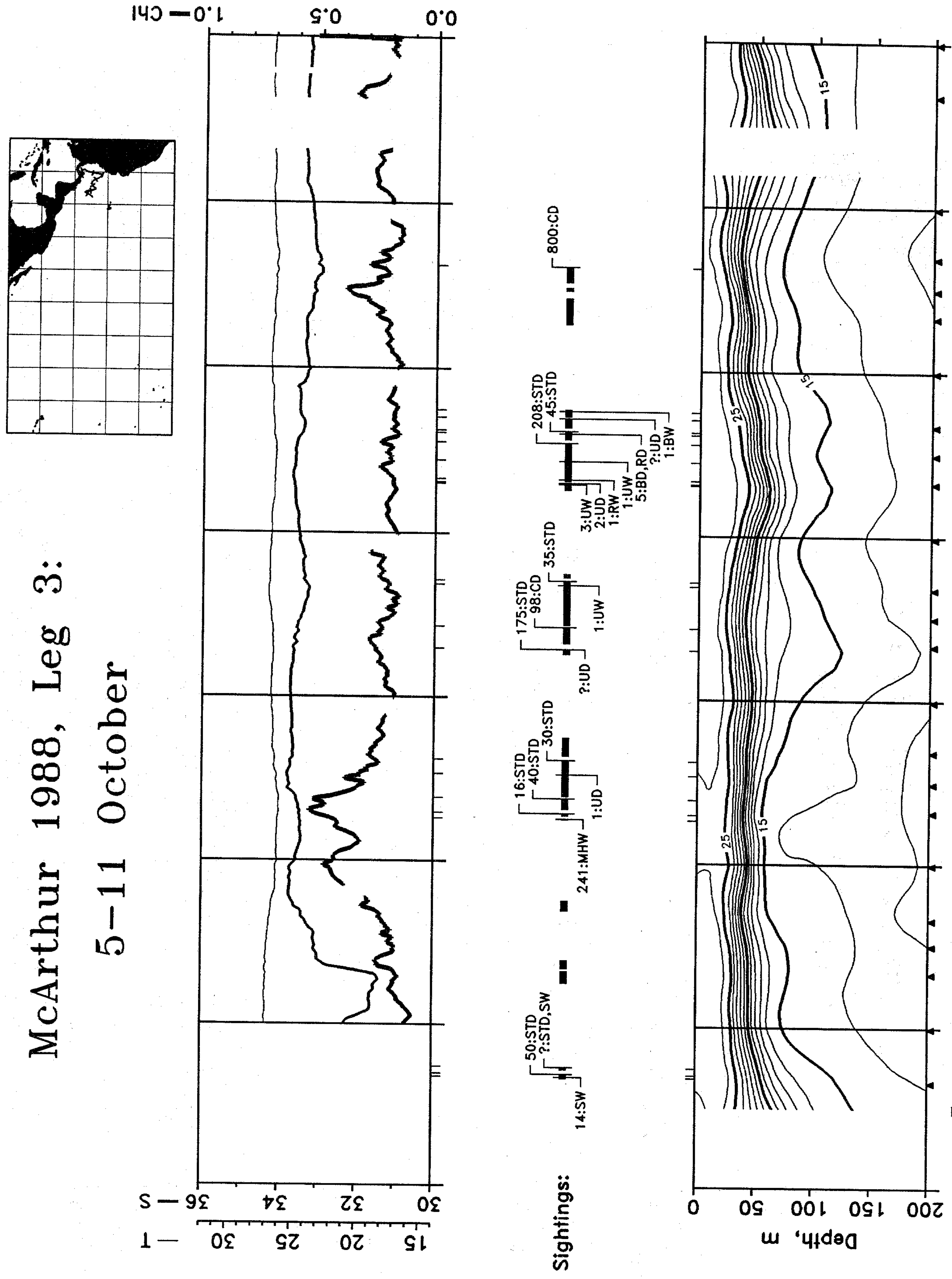




McArthur 1988, Leg 2:
22–28 September

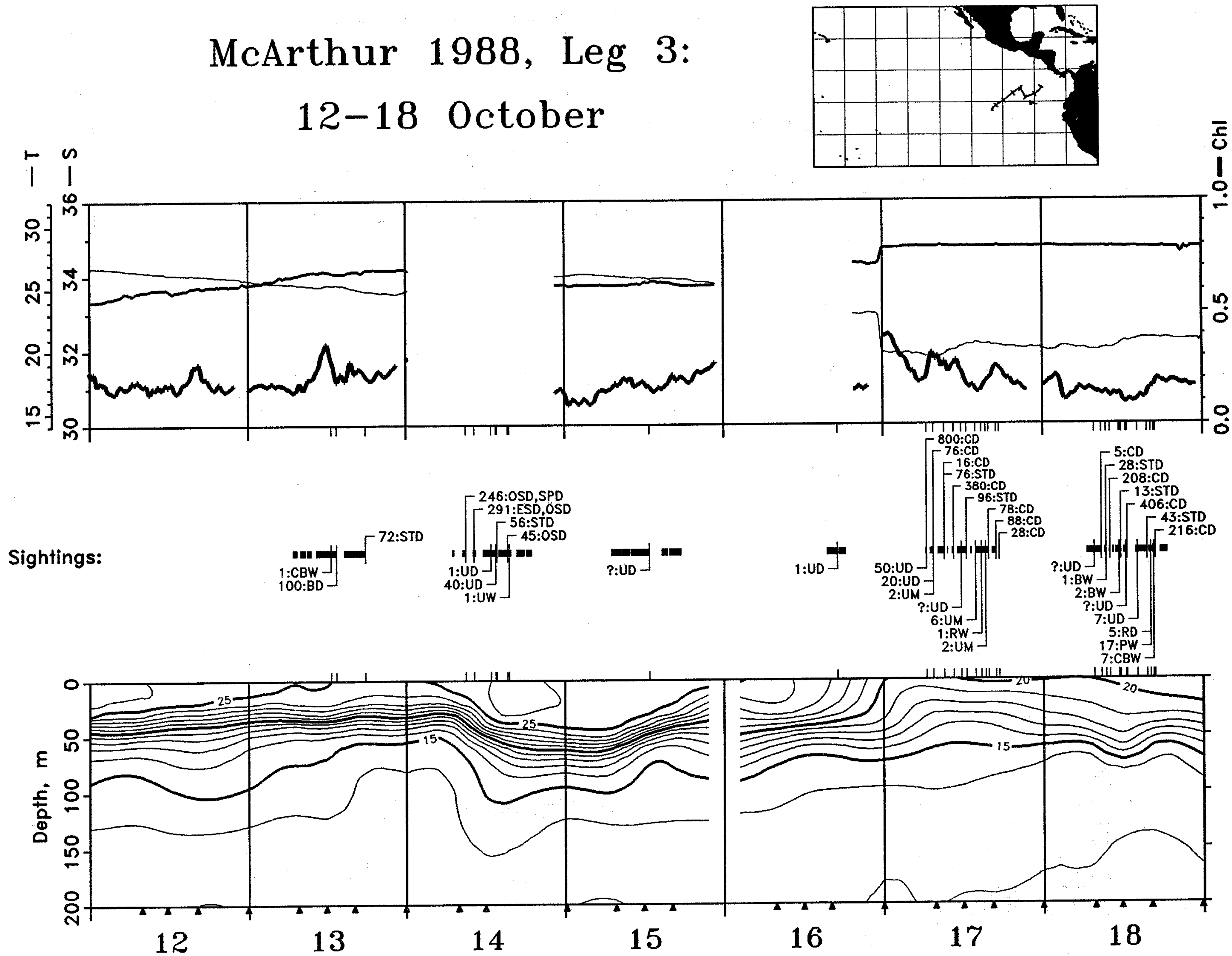




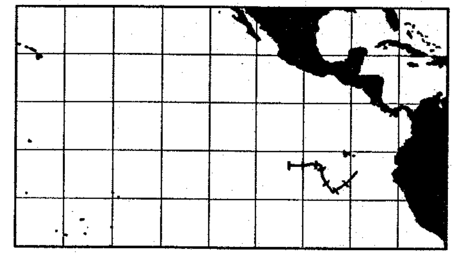


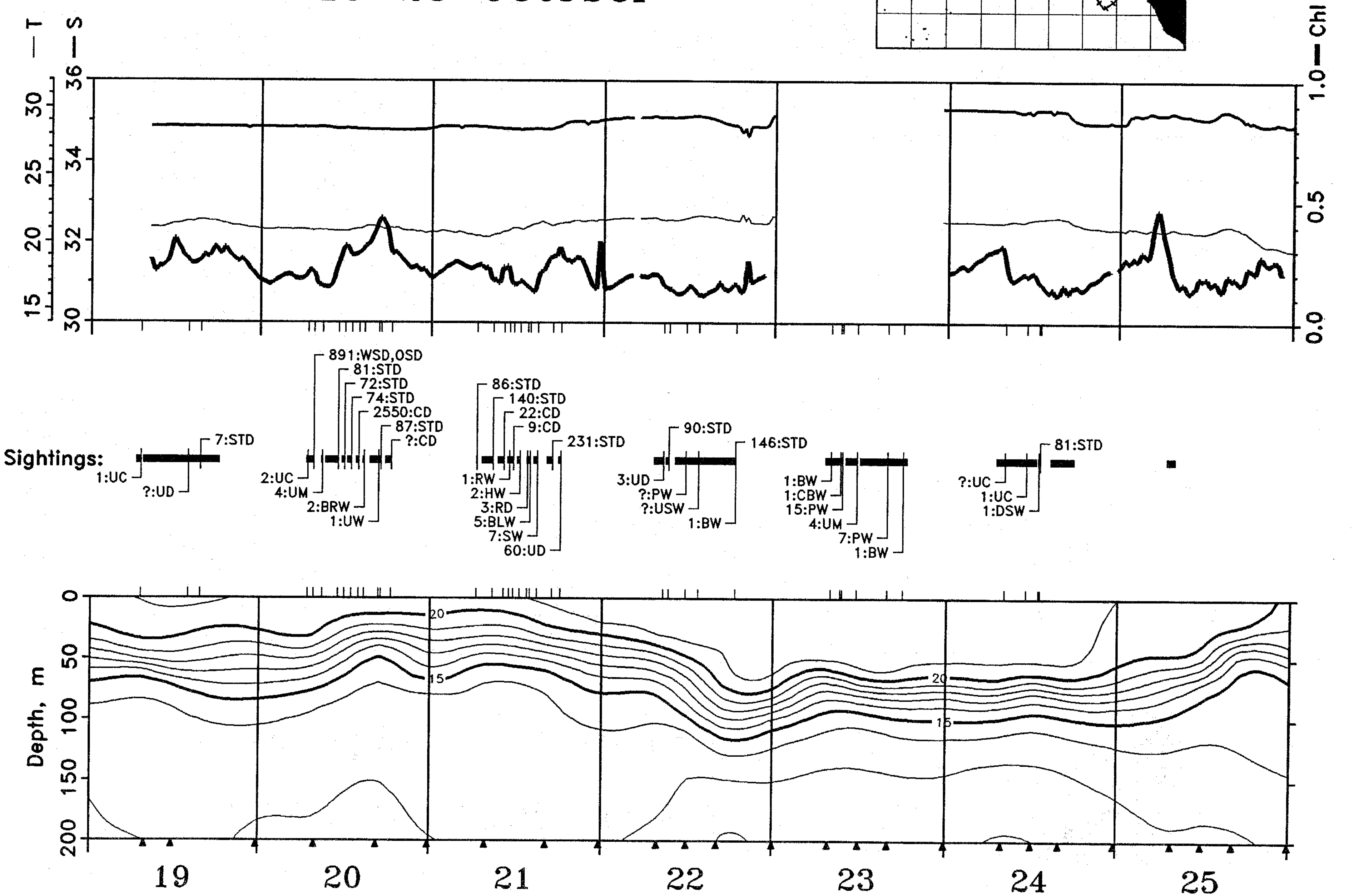
McArthur 1988, Leg 3:
5-11 October
1.0 — Chl
0.5
0.0
T
S
36
34
32
30
25
20
15
Sightings:
14:SW
50:STD
?:STD,SW
241:MHW
16:STD
40:STD
30:STD
1:UD
?:UD
175:STD
98:CD
35:STD
1:UW
3:UW
2:UD
1:RW
1:UW
5:BD,RD
?:UD
1:BW
208:STD
45:STD
800:CD
Depth, m
0
50
100
150
200
5
6
7
8
9
10
11

McArthur 1988, Leg 3:
12–18 October

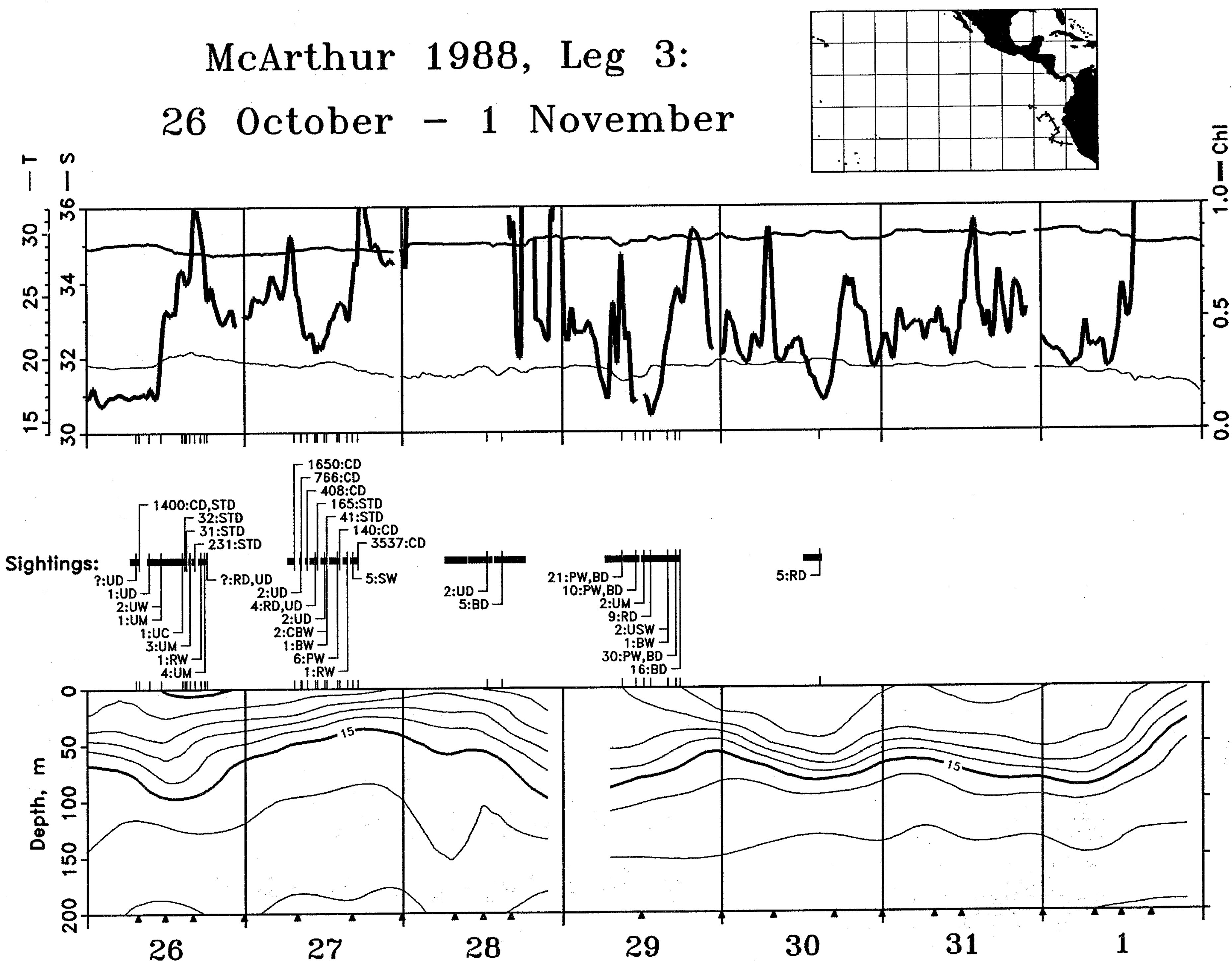


McArthur 1988, Leg 3:
19–25 October

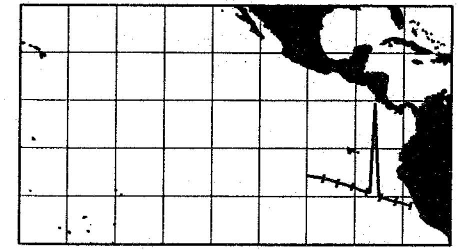


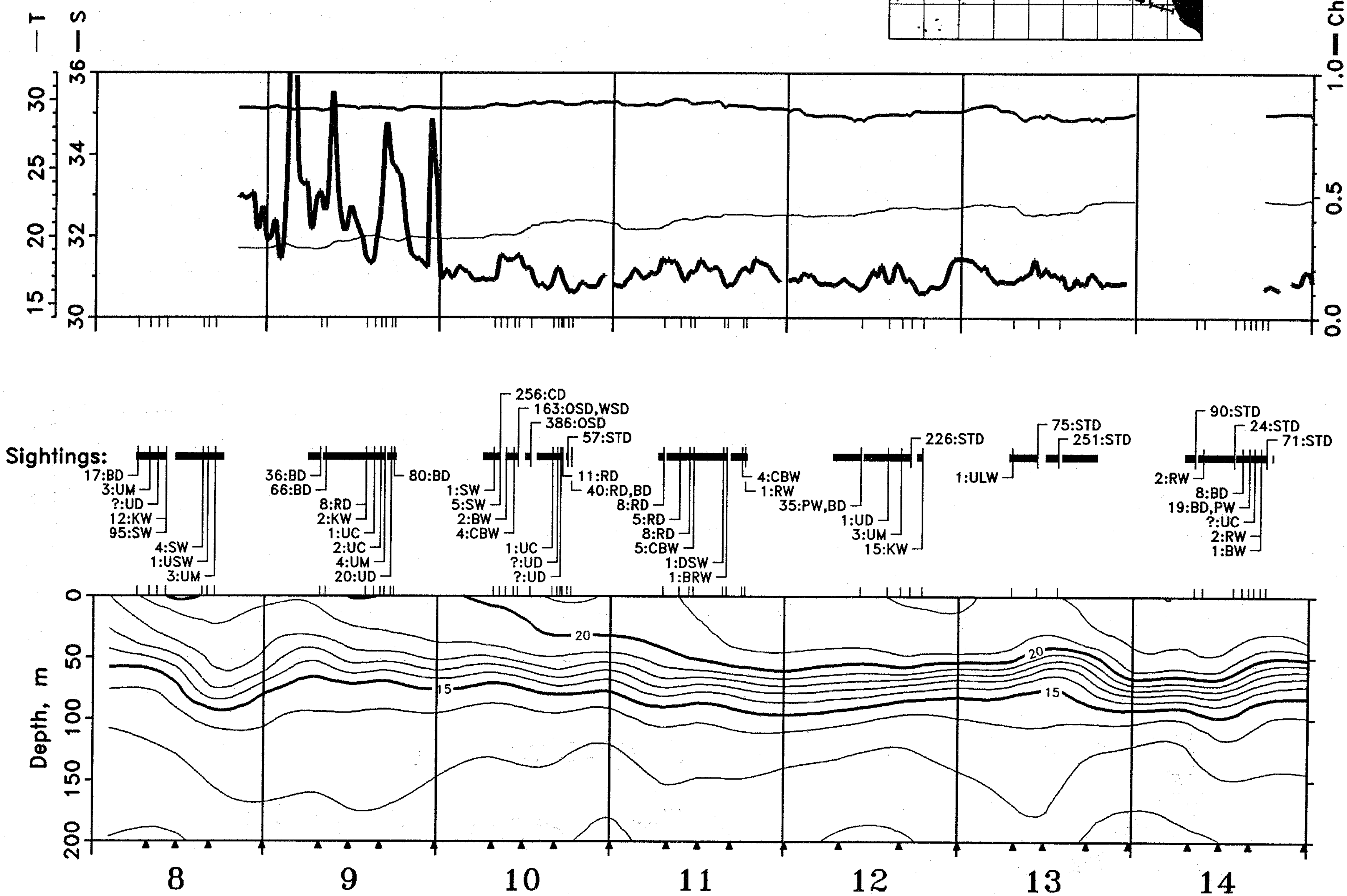


McArthur 1988, Leg 3:
26 October – 1 November

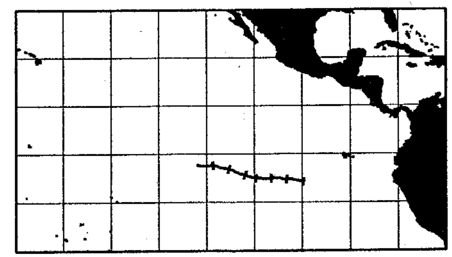


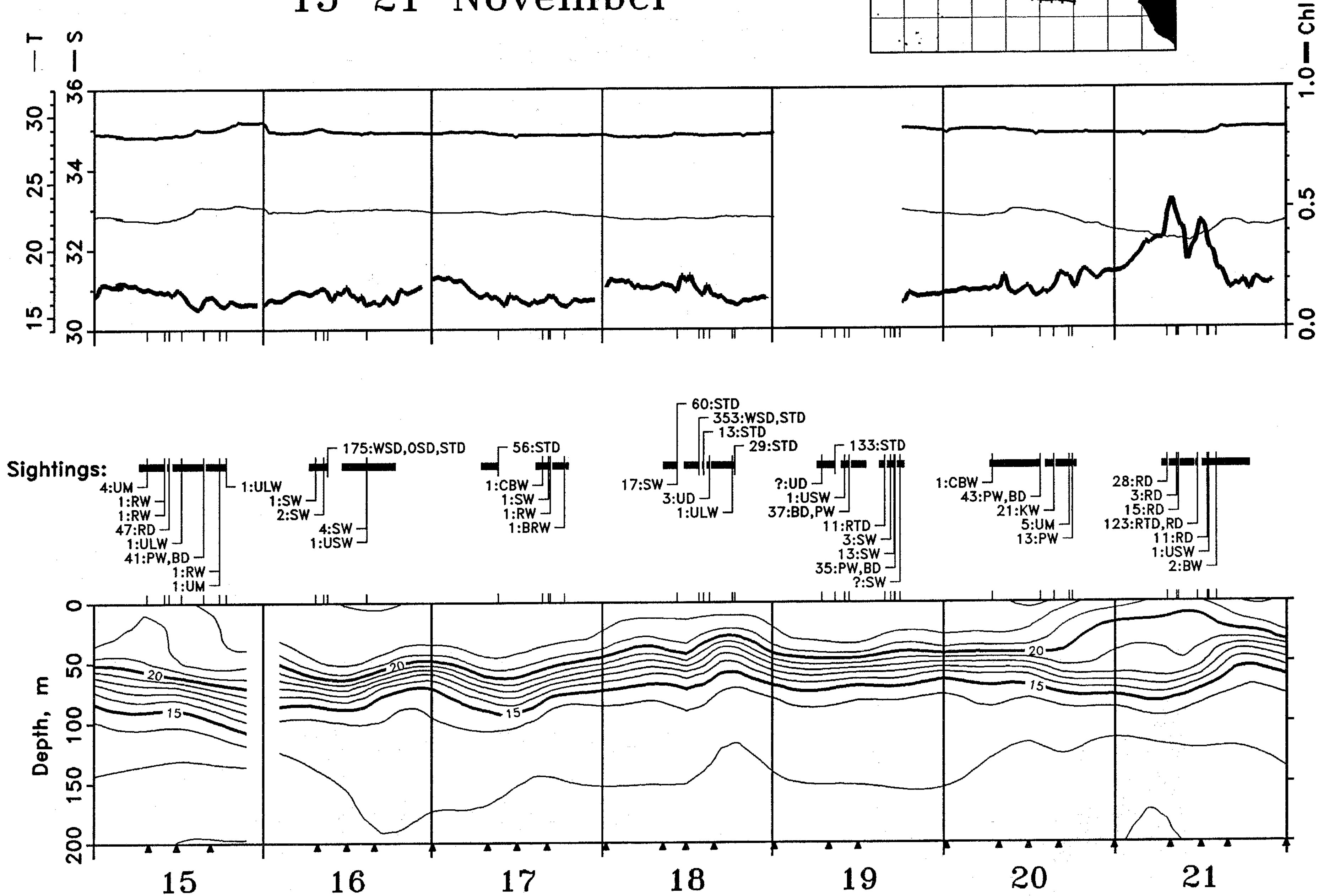
McArthur 1988, Leg 4:
8–14 November



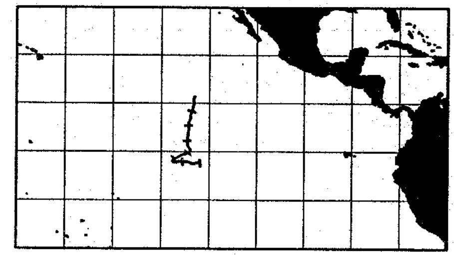


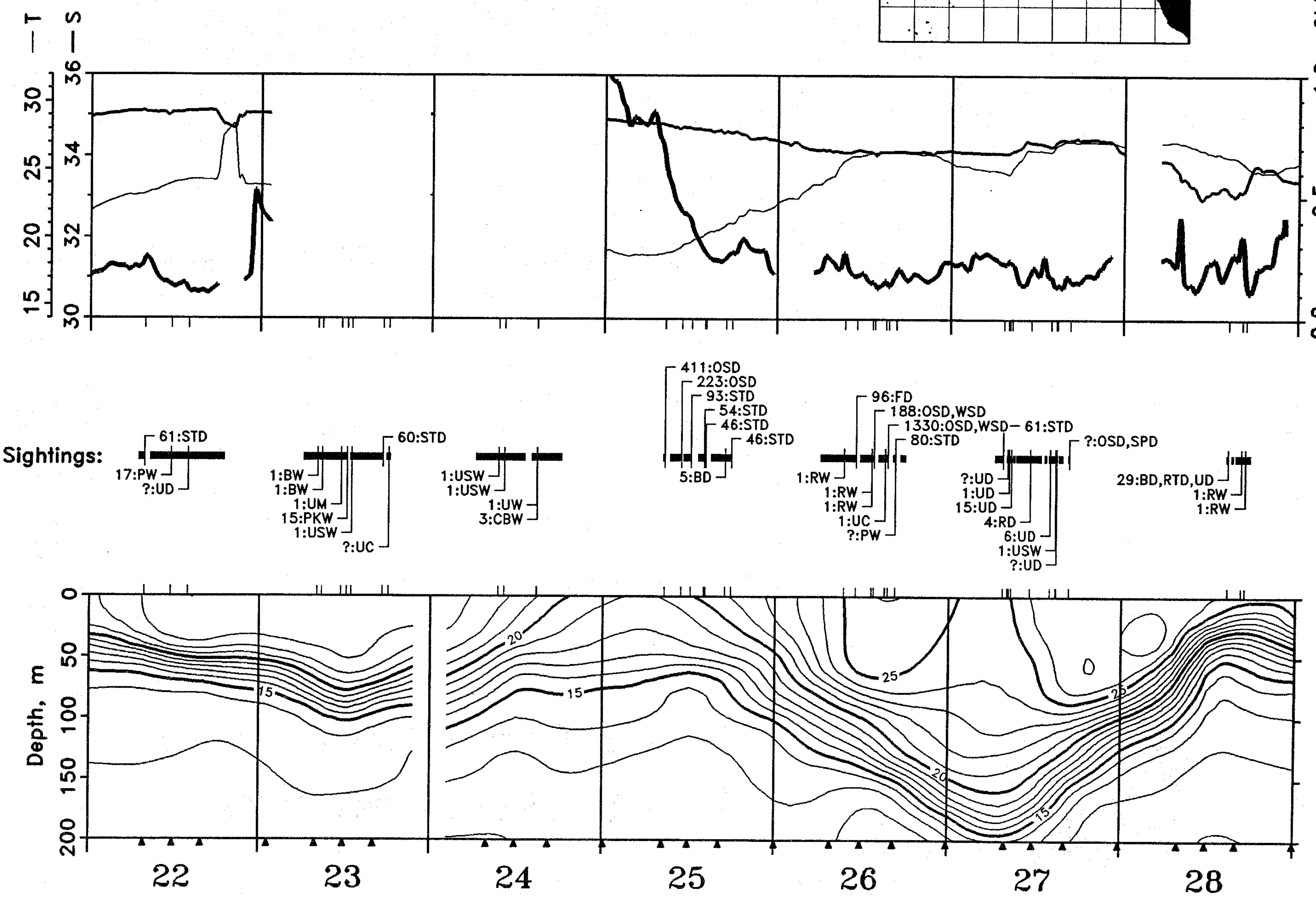
McArthur 1988, Leg 4:
15–21 November



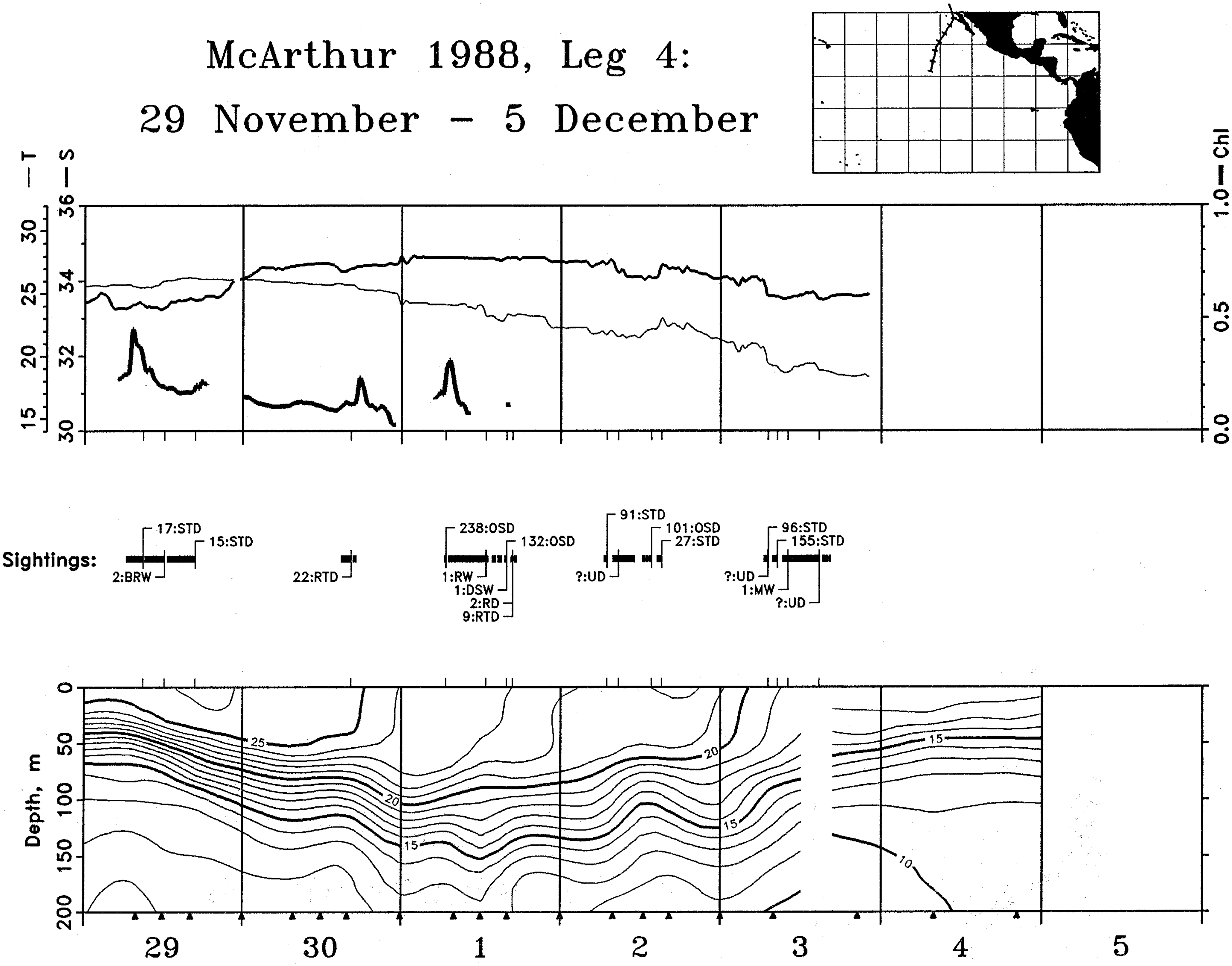


McArthur 1988, Leg 4:
22–28 November

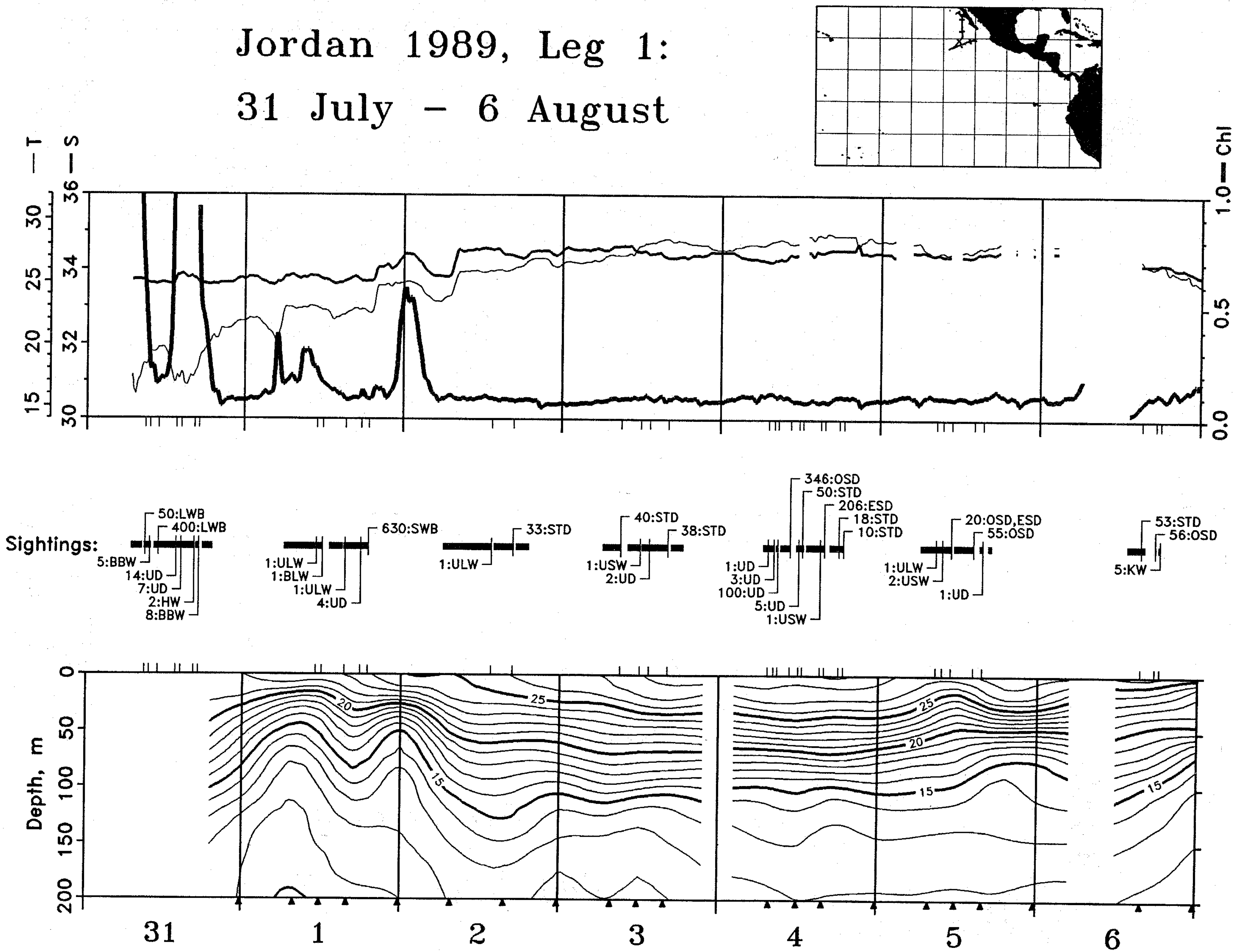




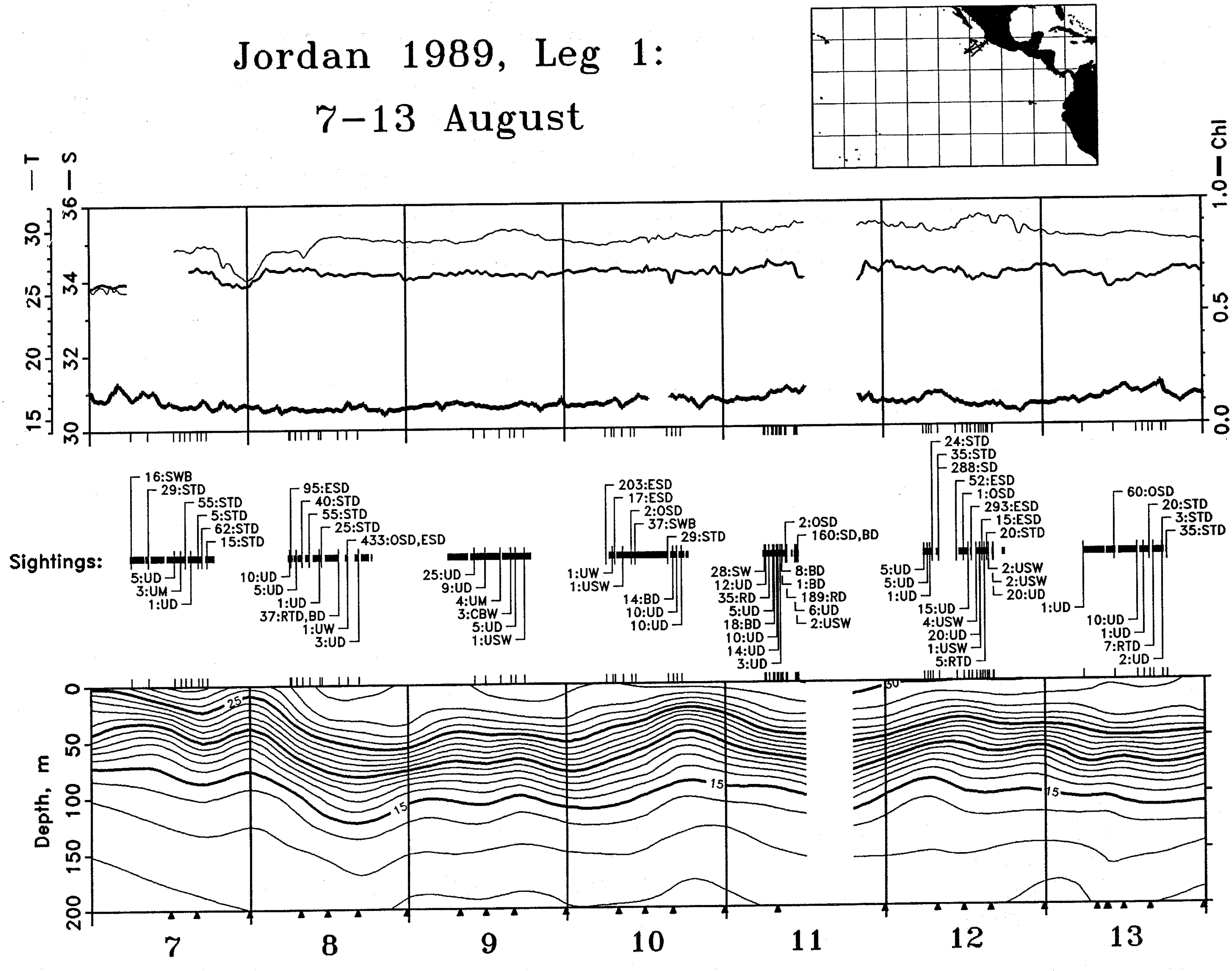
McArthur 1988, Leg 4: 29 November – 5 December



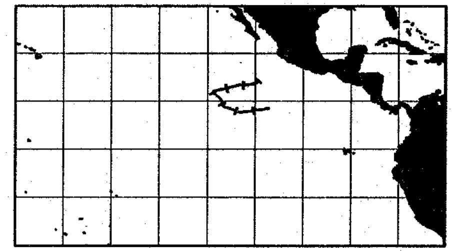
Jordan 1989, Leg 1:
31 July – 6 August

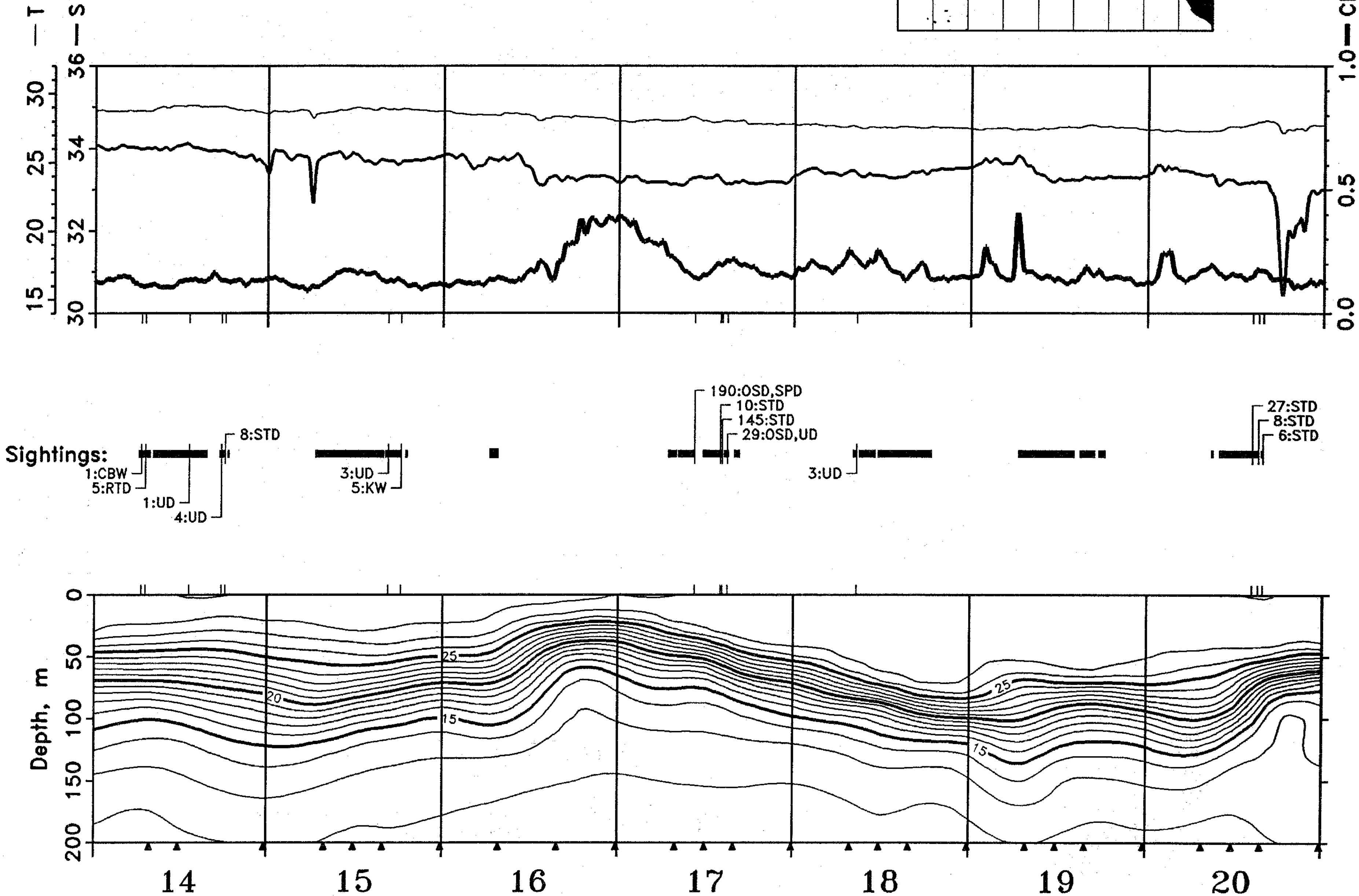


Jordan 1989, Leg 1:
7–13 August

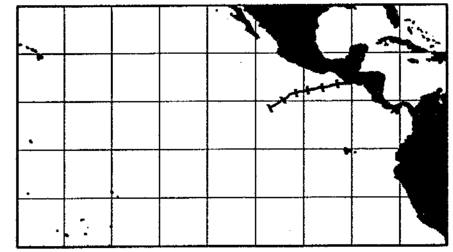


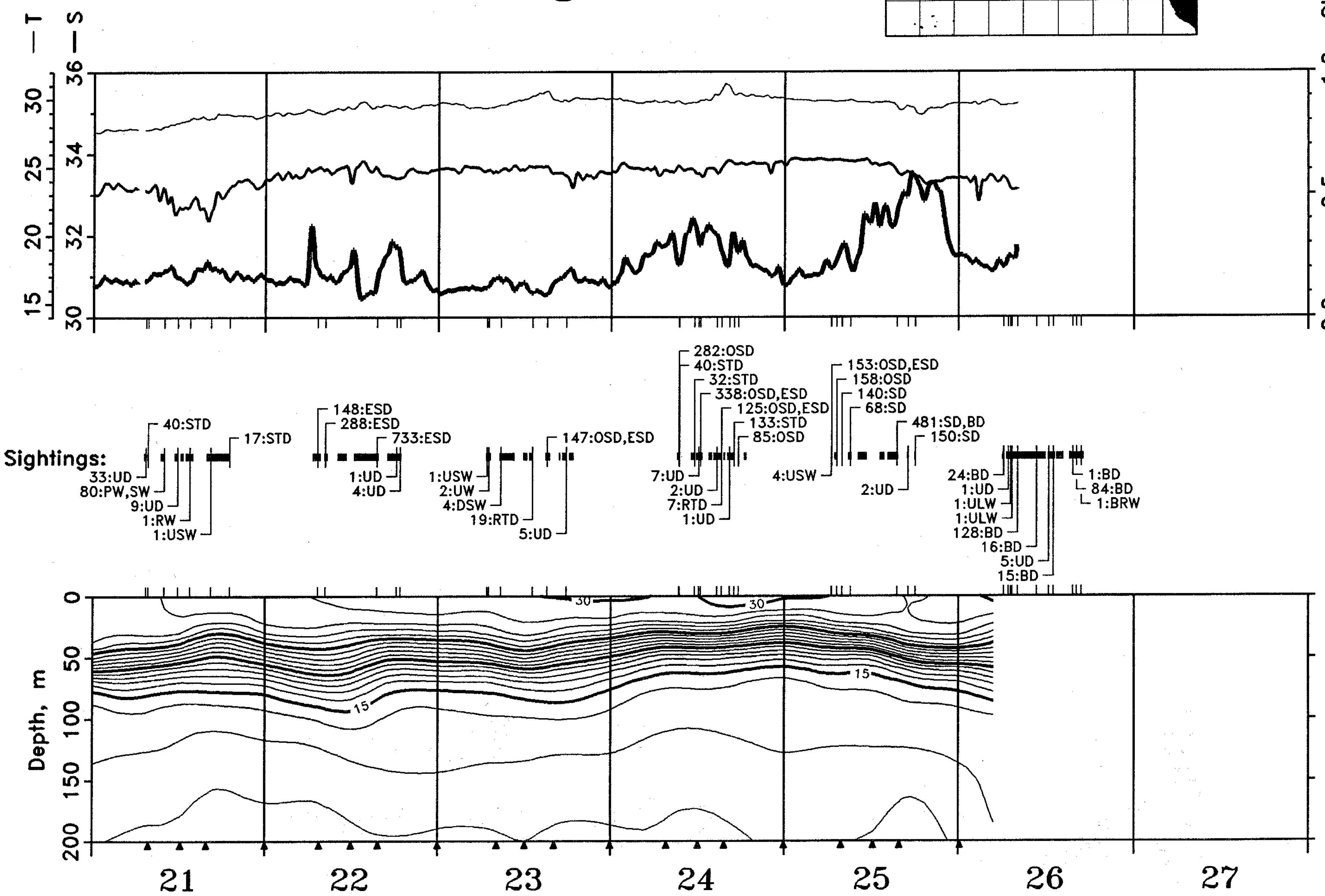
Jordan 1989, Leg 1:
14–20 August



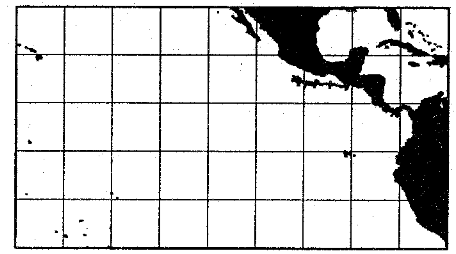


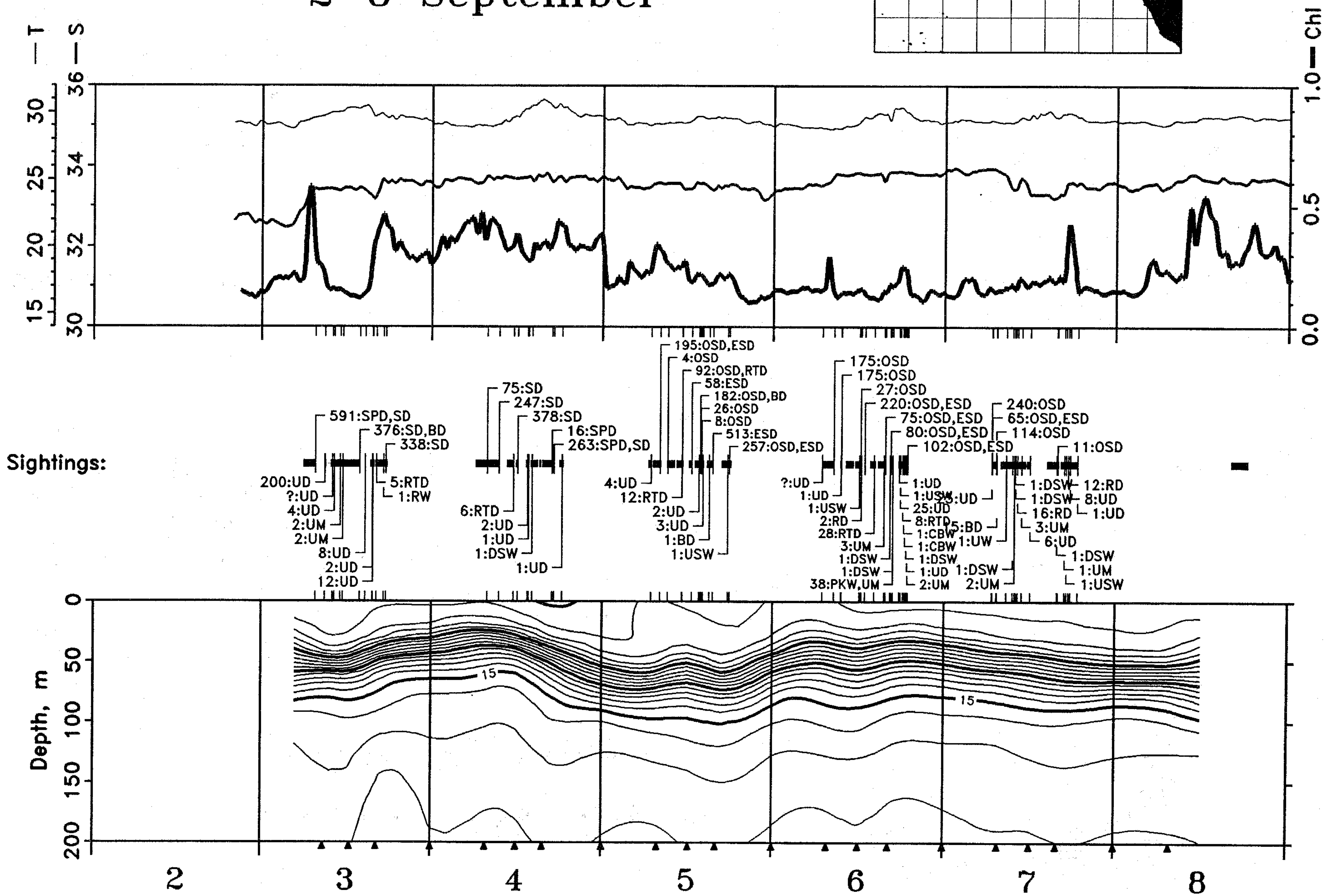
Jordan 1989, Leg 1:
21–27 August



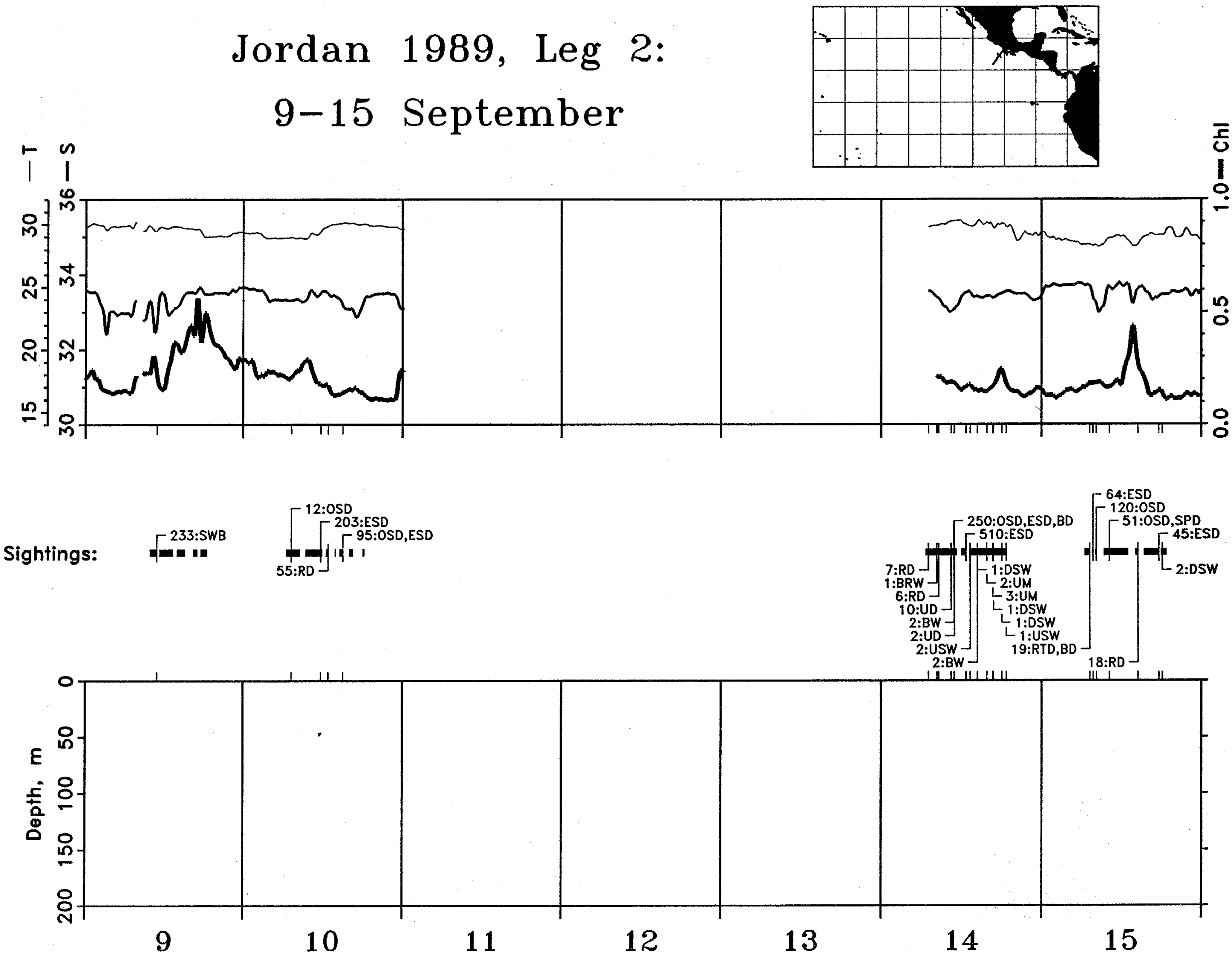


Jordan 1989, Leg 2:
2–8 September

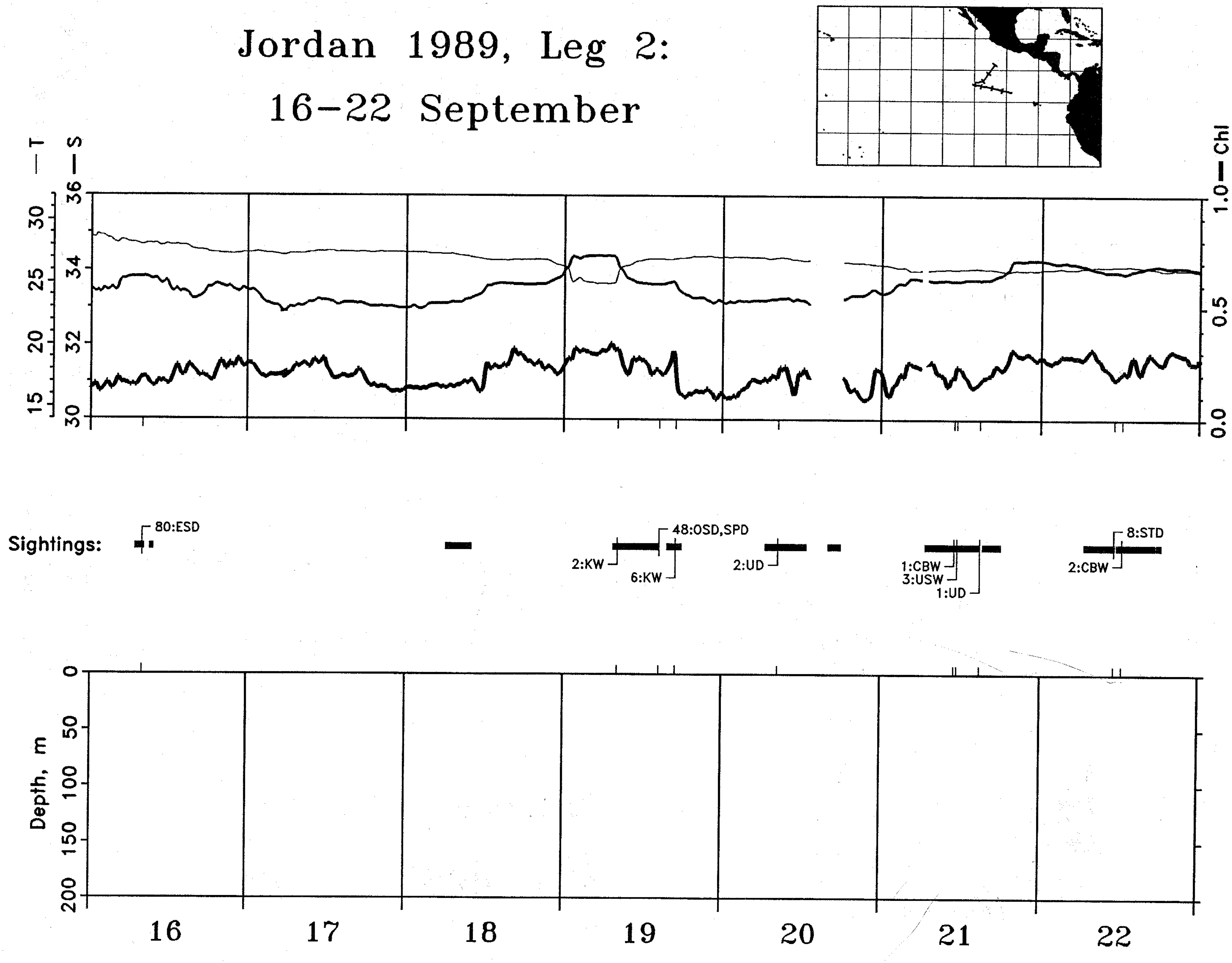




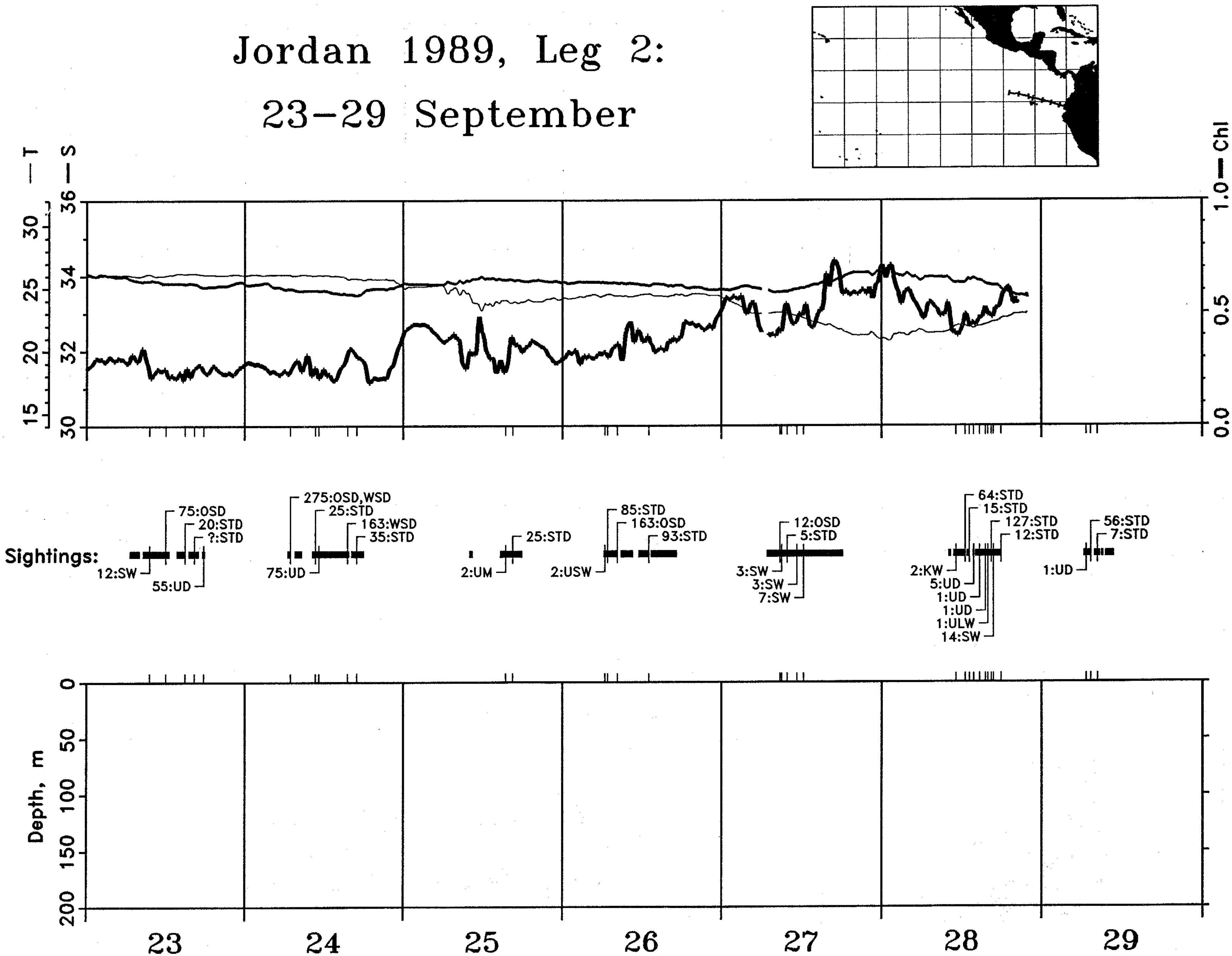
Jordan 1989, Leg 2:
9–15 September



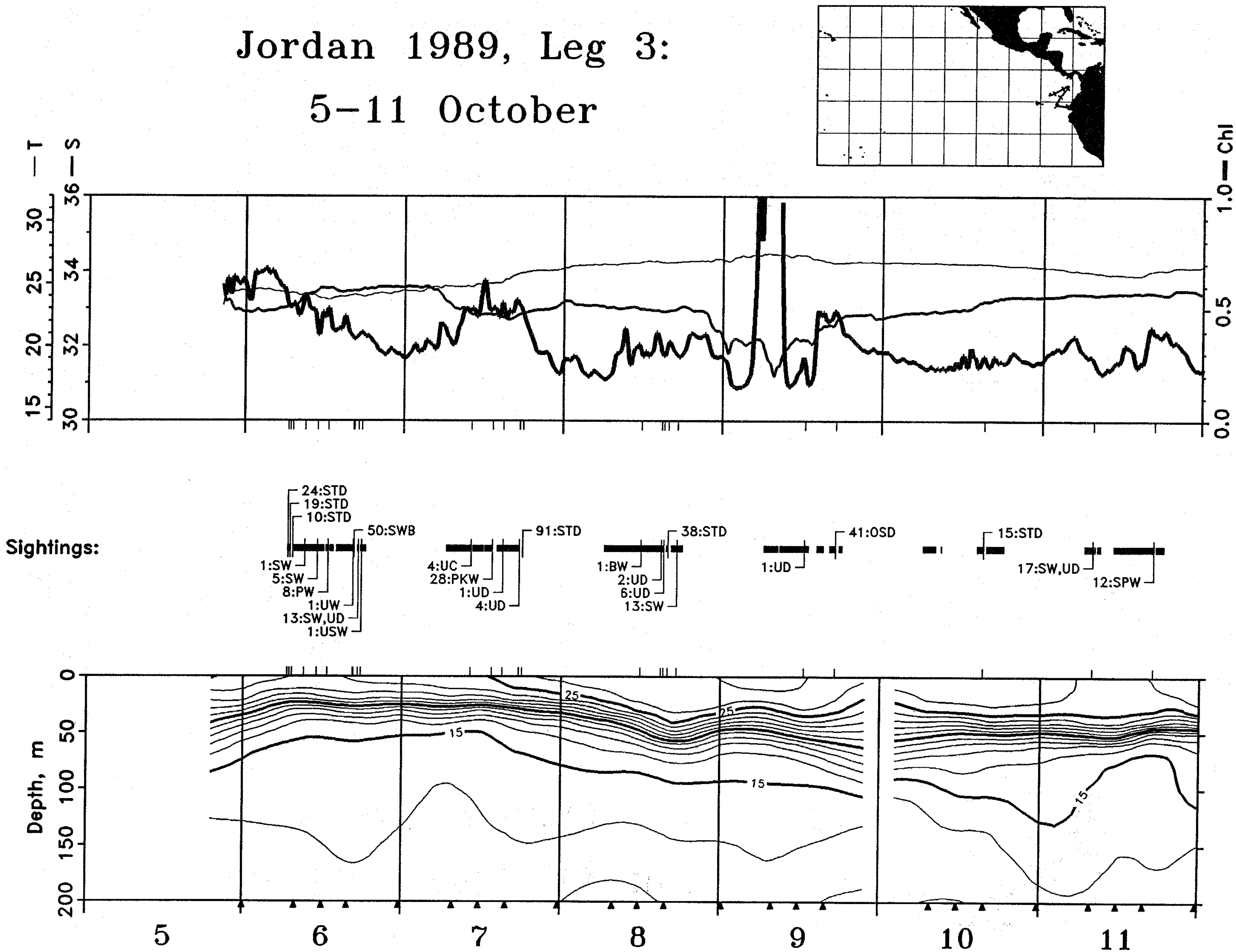
Jordan 1989, Leg 2:
16–22 September



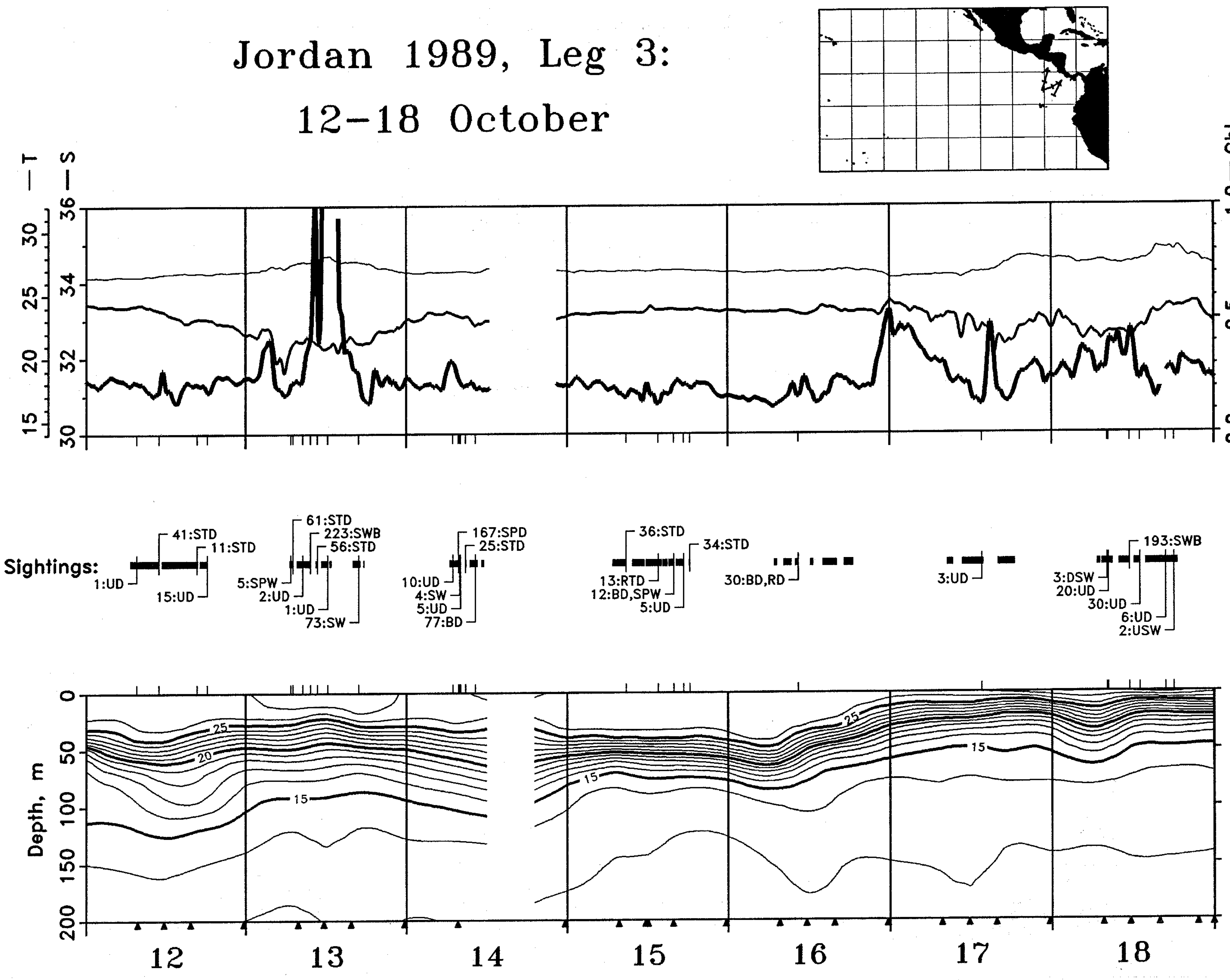
Jordan 1989, Leg 2:
23–29 September



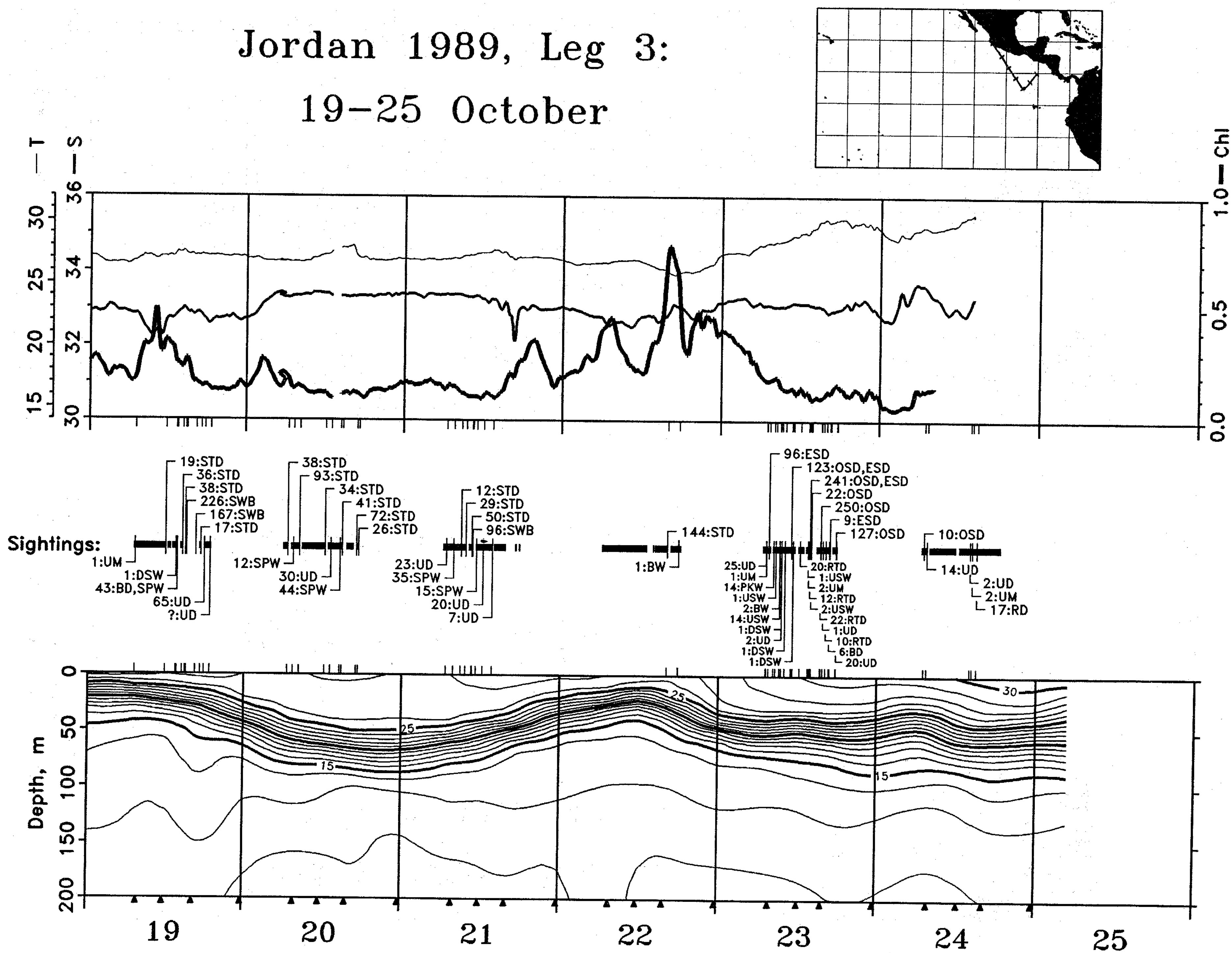
Jordan 1989, Leg 3:
5–11 October



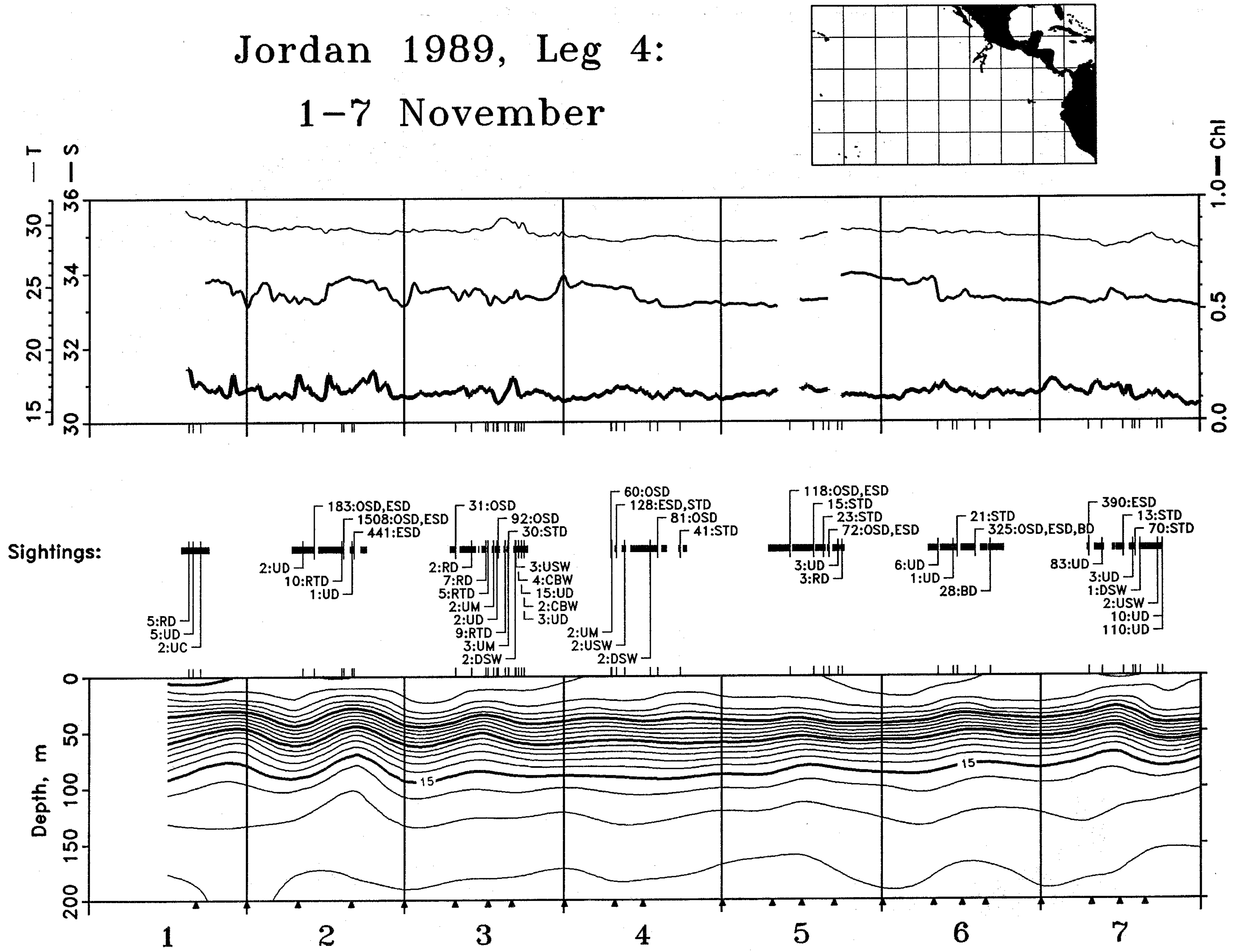
Jordan 1989, Leg 3:
12–18 October



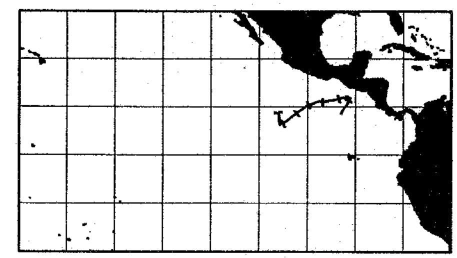
Jordan 1989, Leg 3:
19–25 October

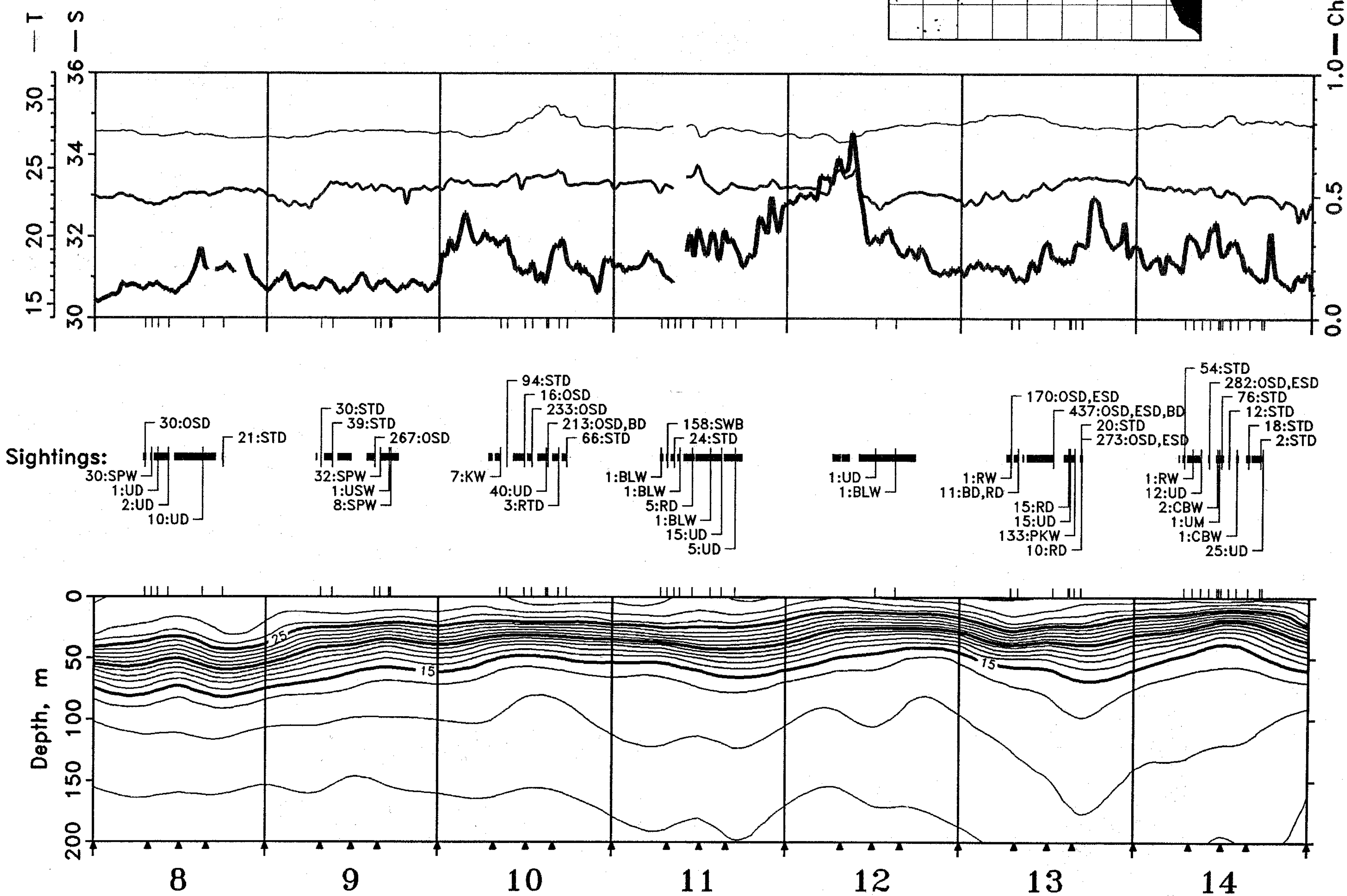


Jordan 1989, Leg 4:
1–7 November

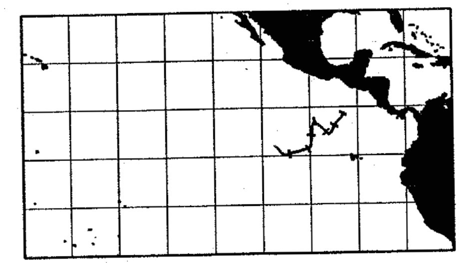


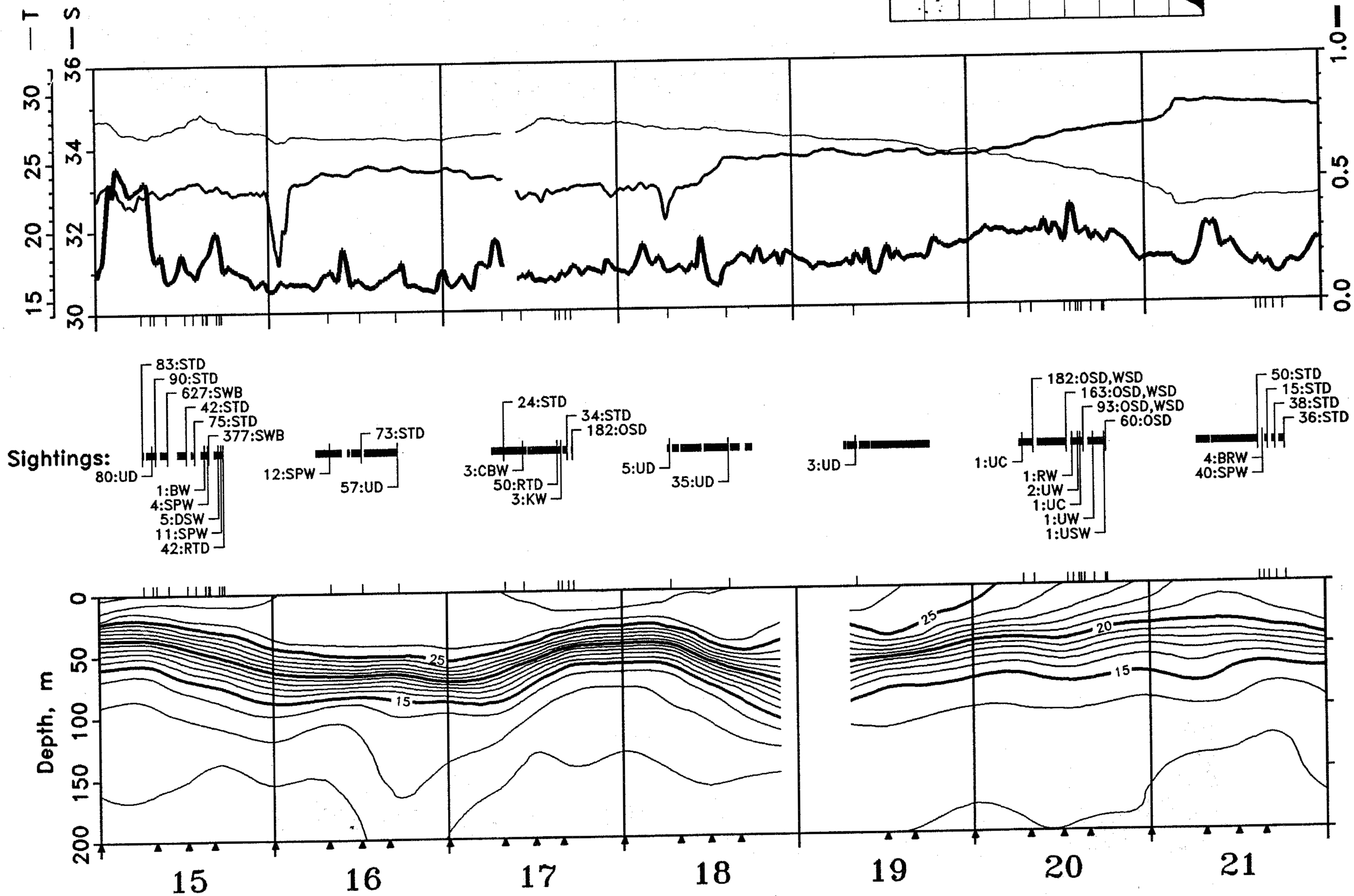
Jordan 1989, Leg 4:
8–14 November



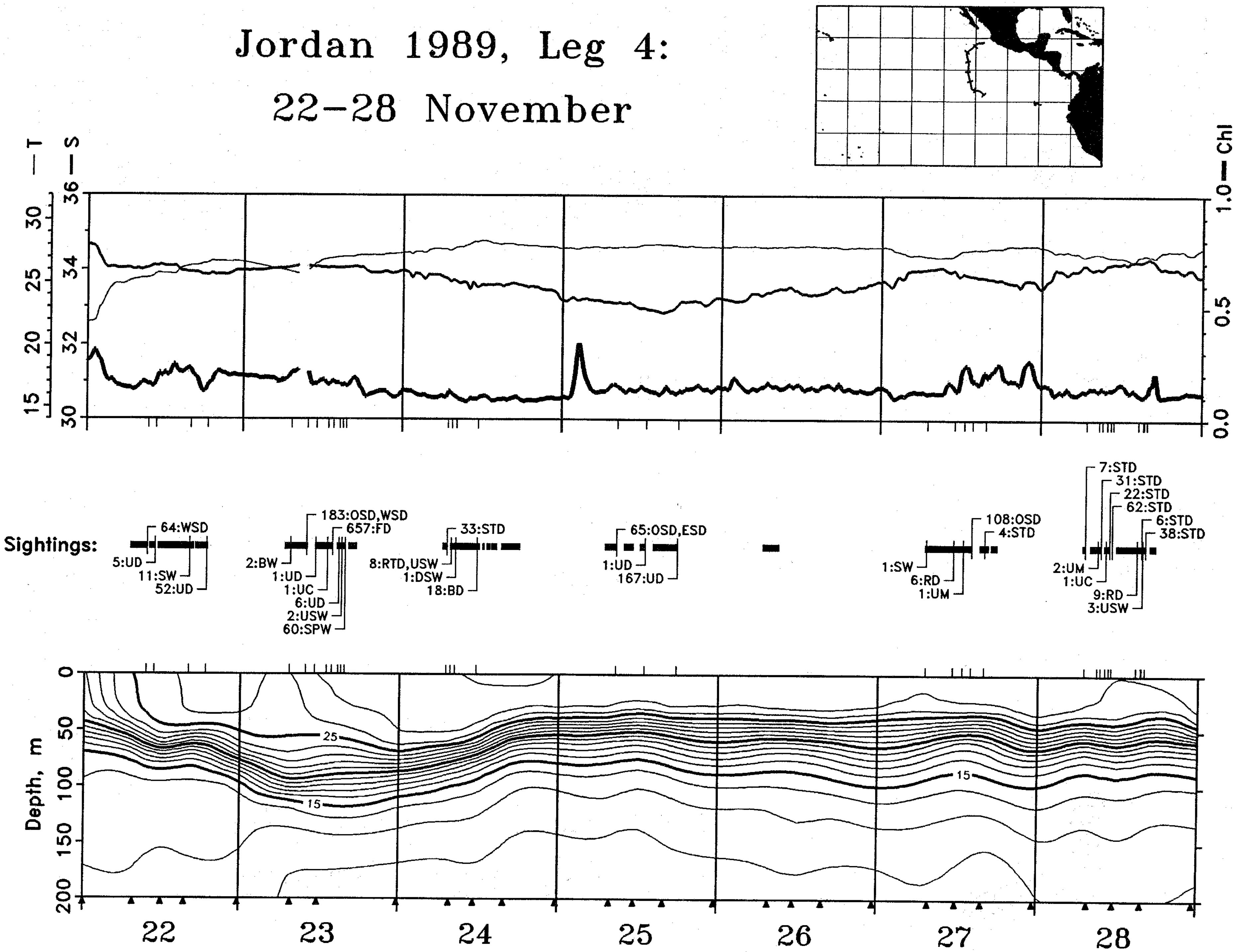


Jordan 1989, Leg 4:
15–21 November

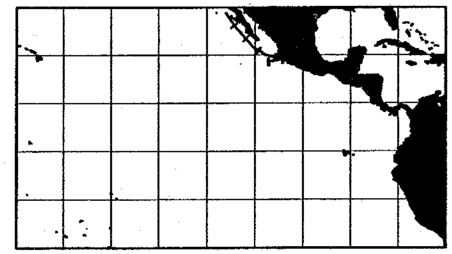


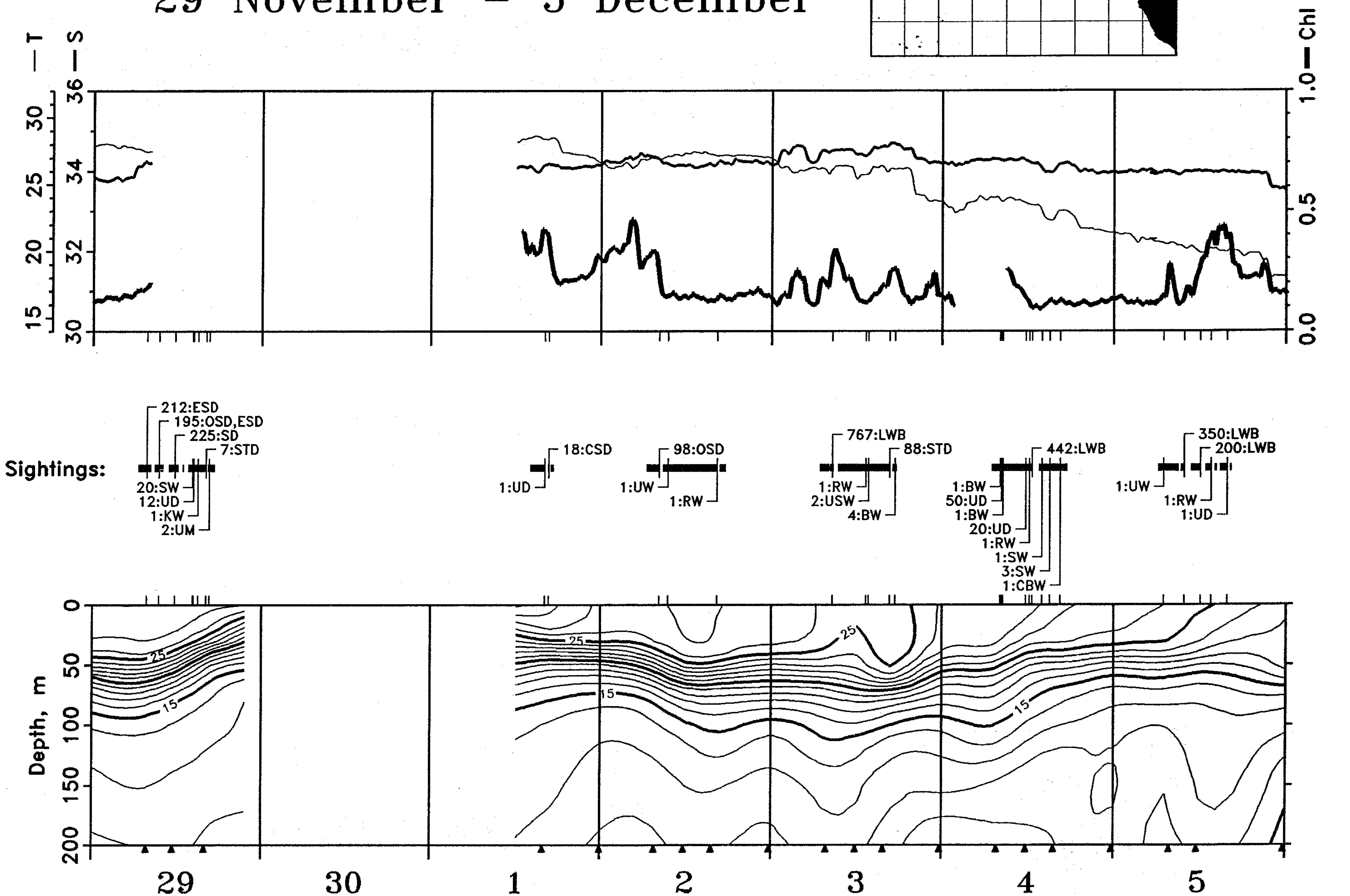


Jordan 1989, Leg 4:
22–28 November

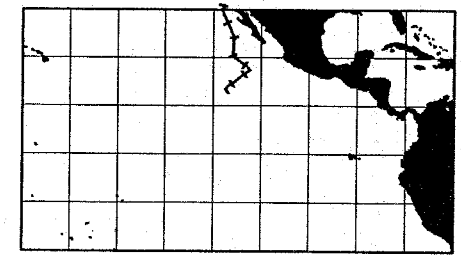


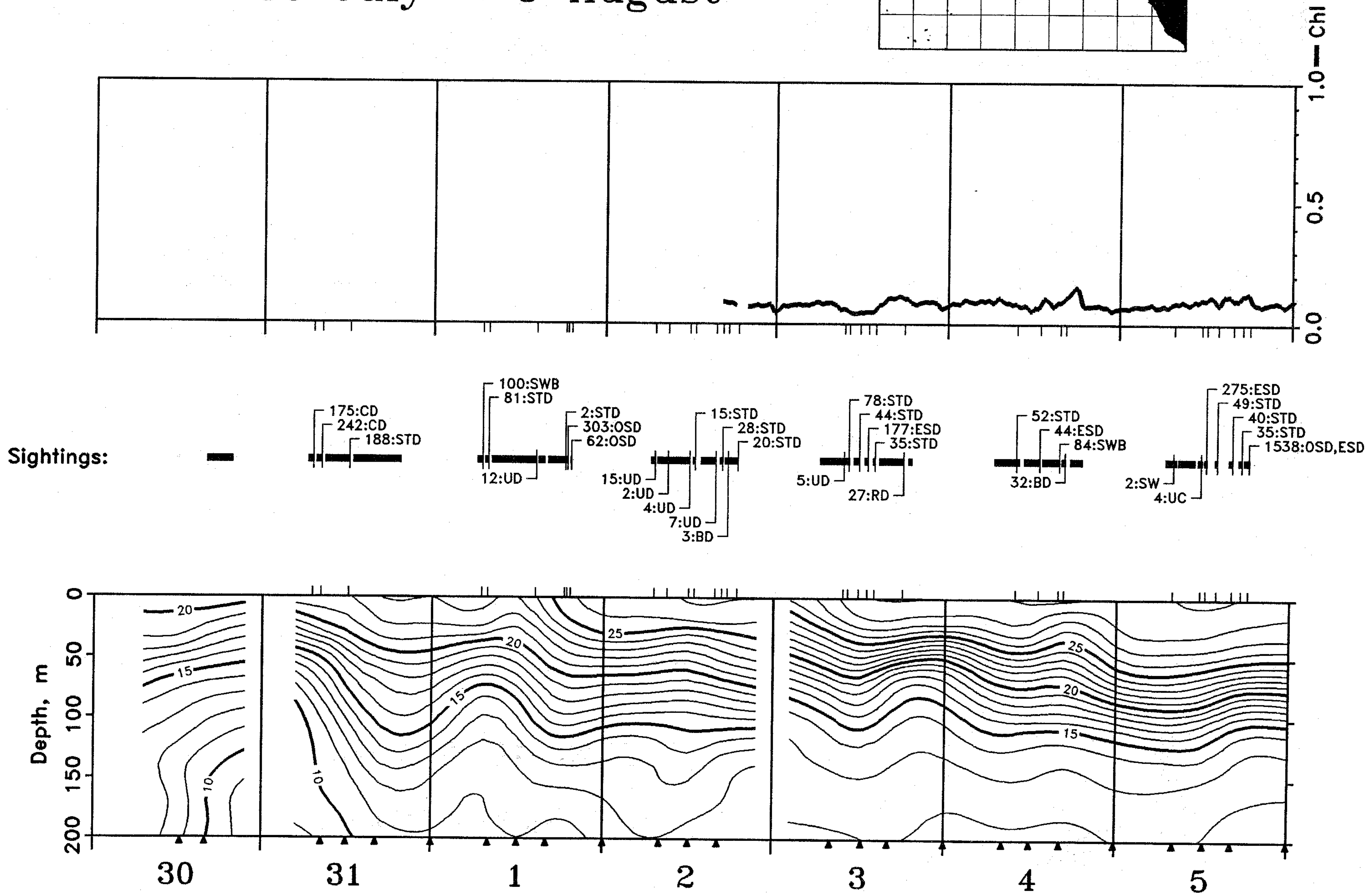
Jordan 1989, Leg 4:
29 November – 5 December



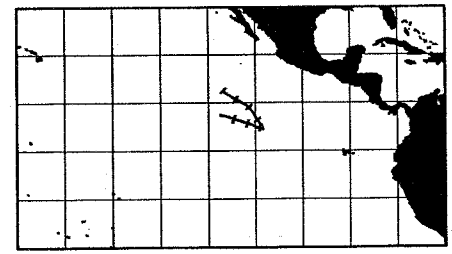


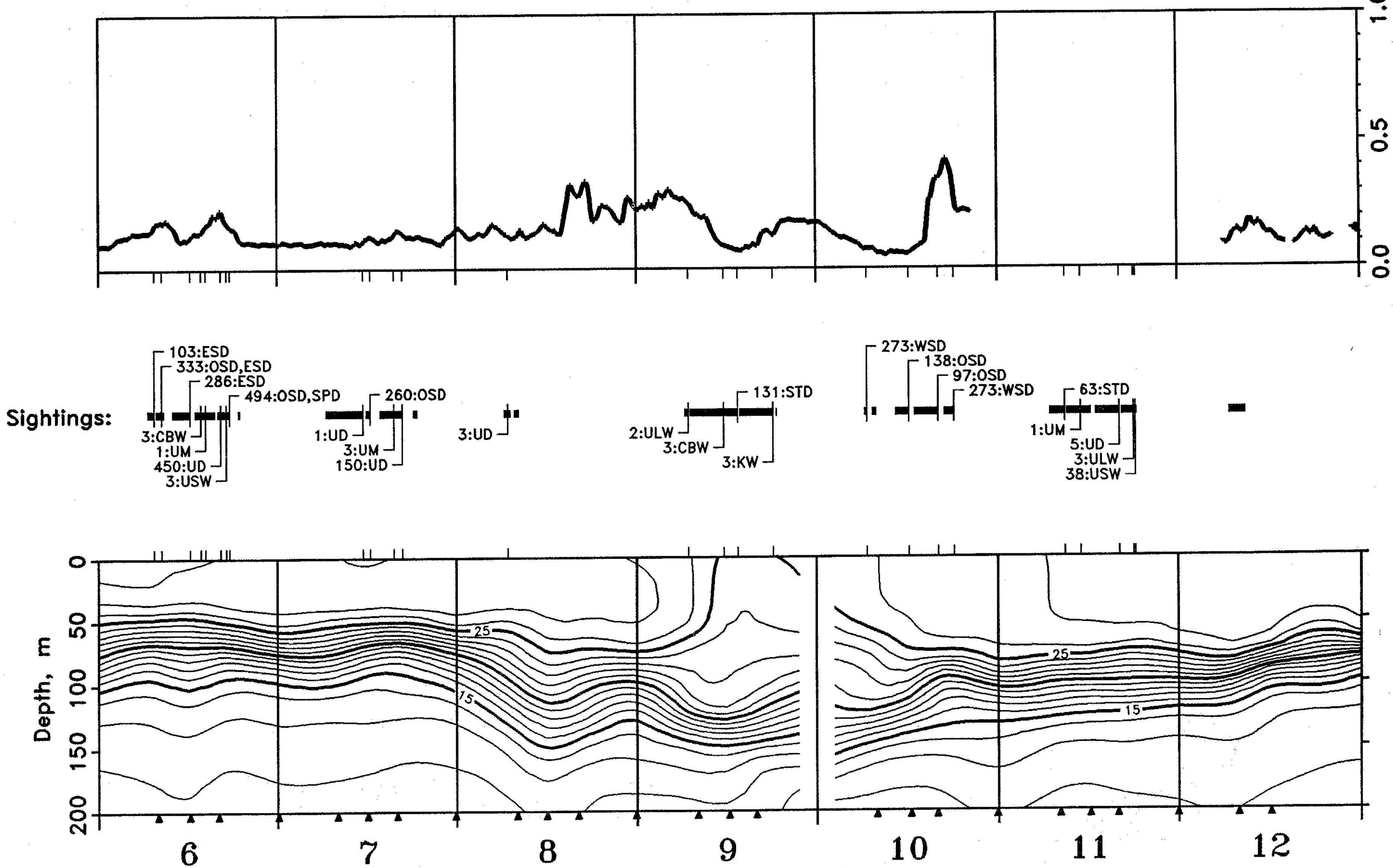
McArthur 1989, Leg 1:
30 July – 5 August



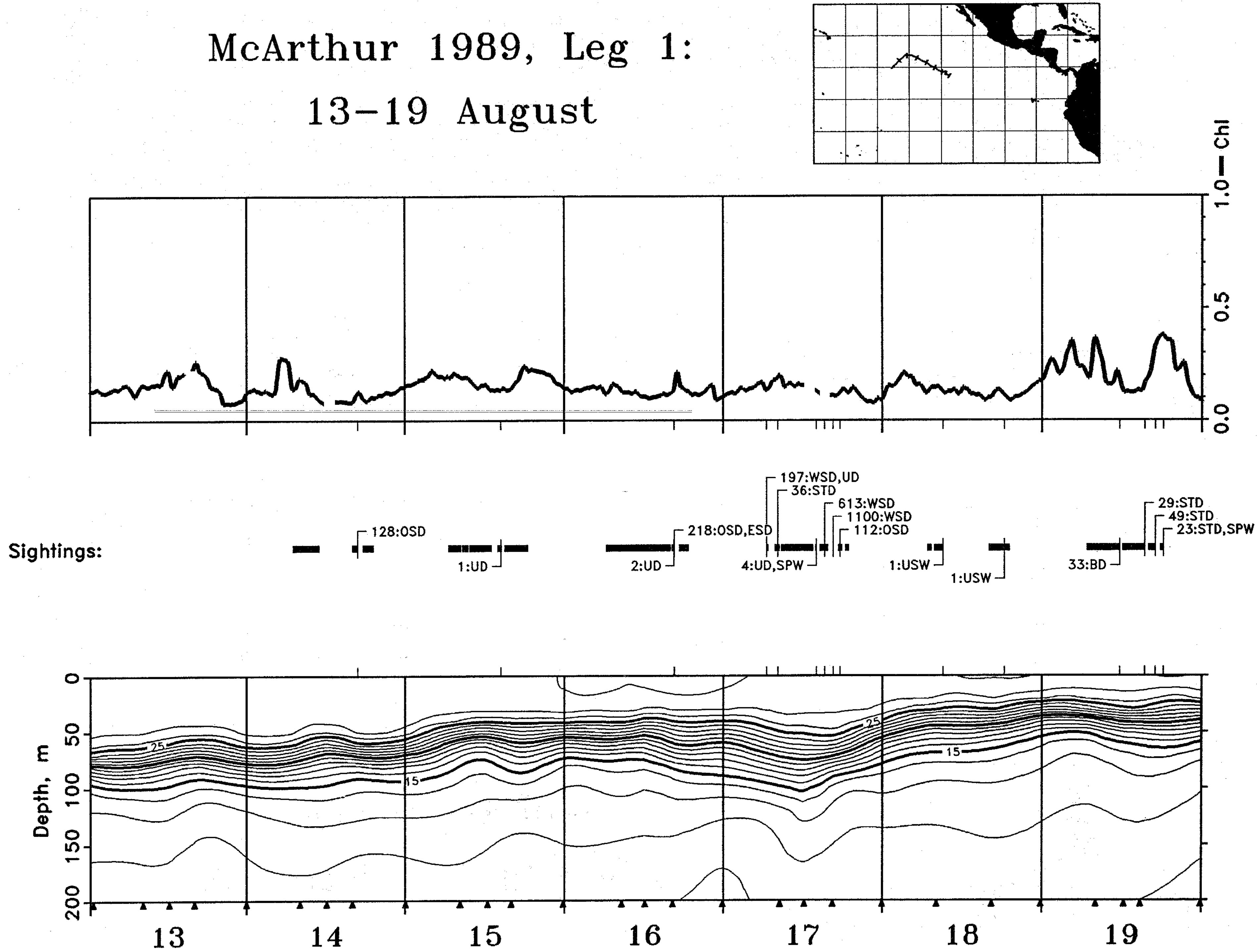


McArthur 1989, Leg 1:
6–12 August

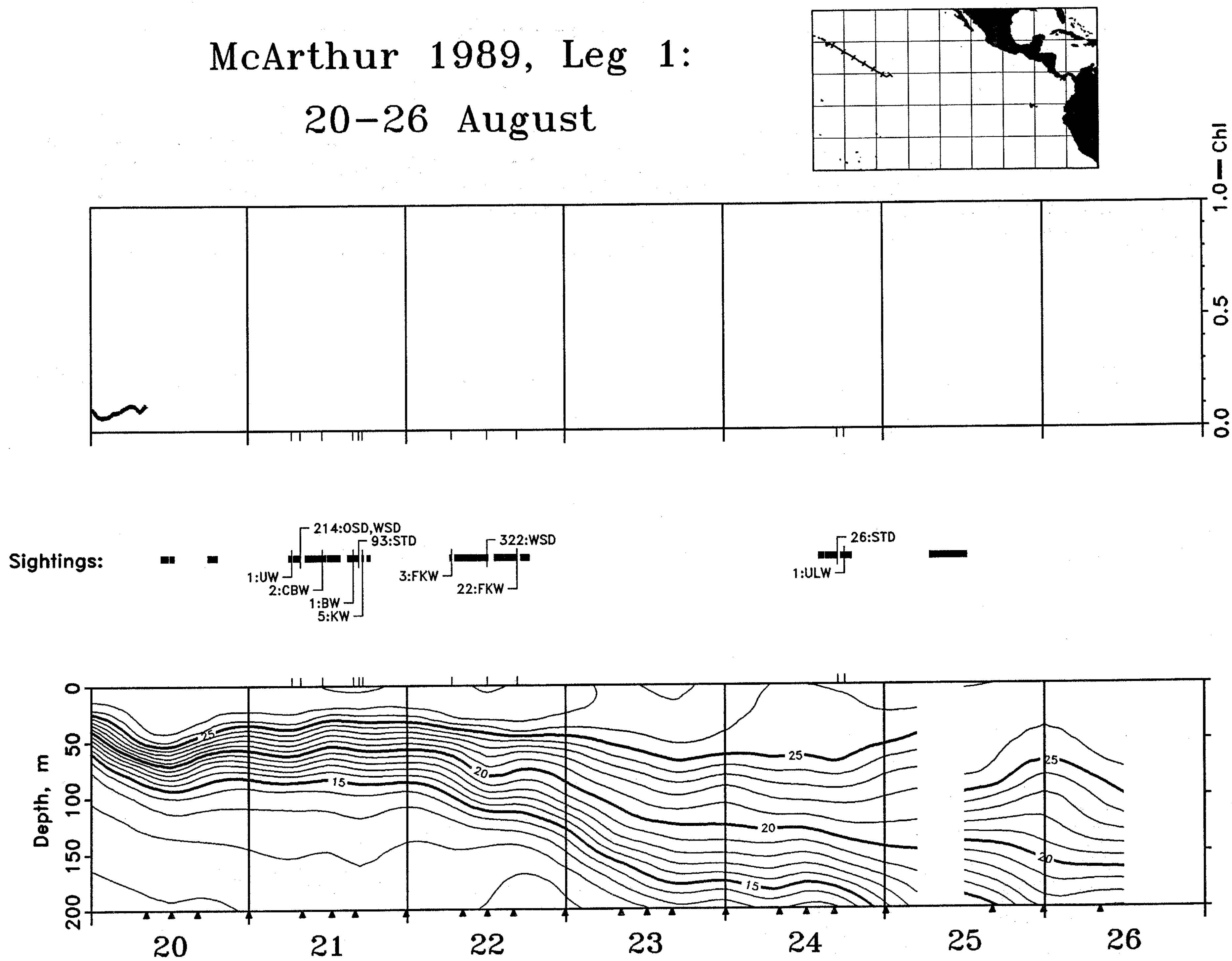




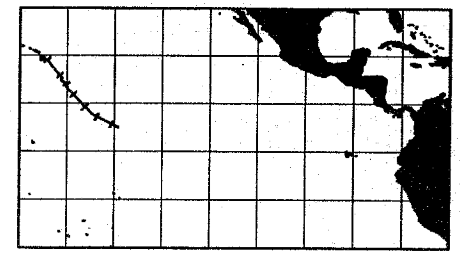
McArthur 1989, Leg 1:
13–19 August

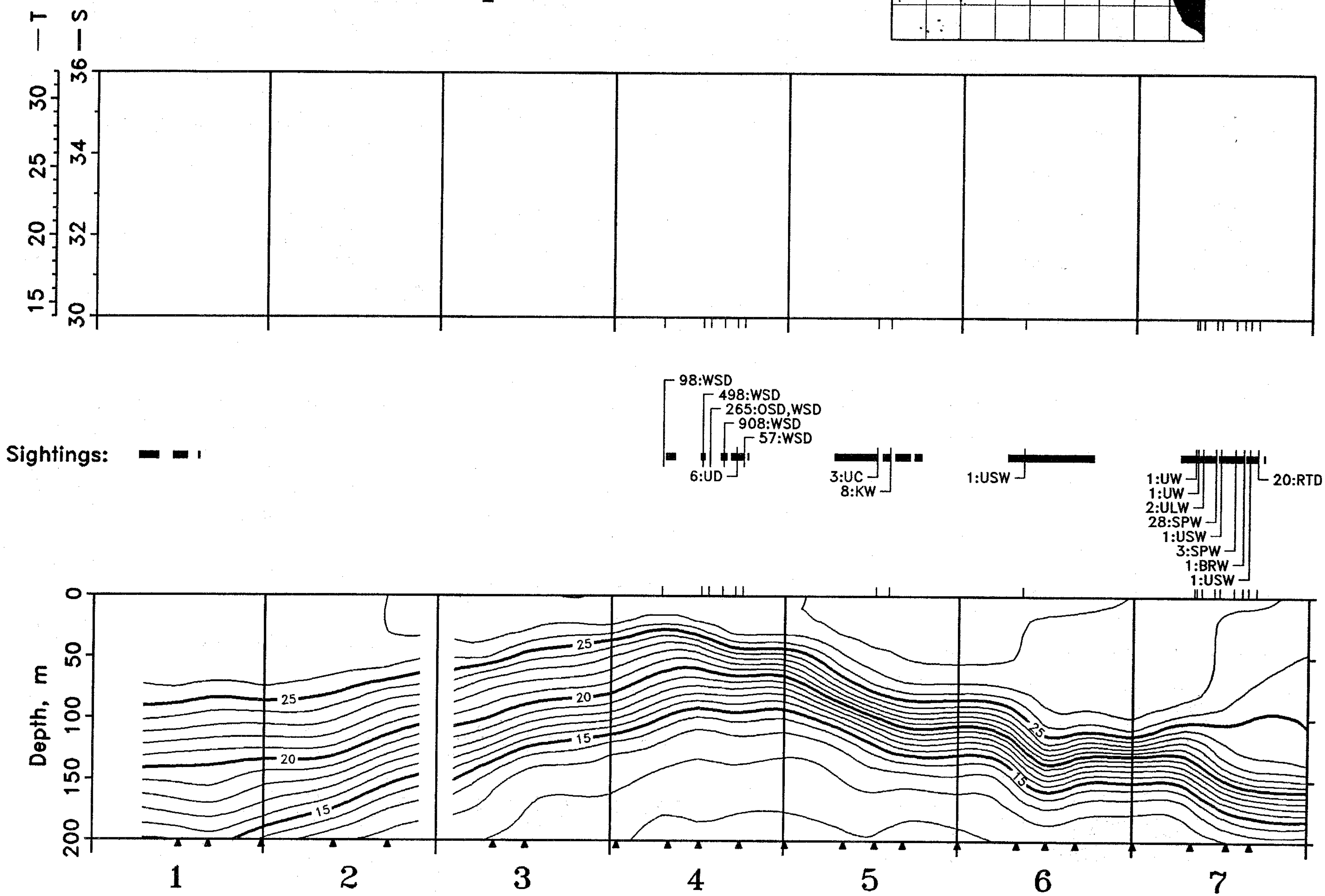


McArthur 1989, Leg 1:
20–26 August

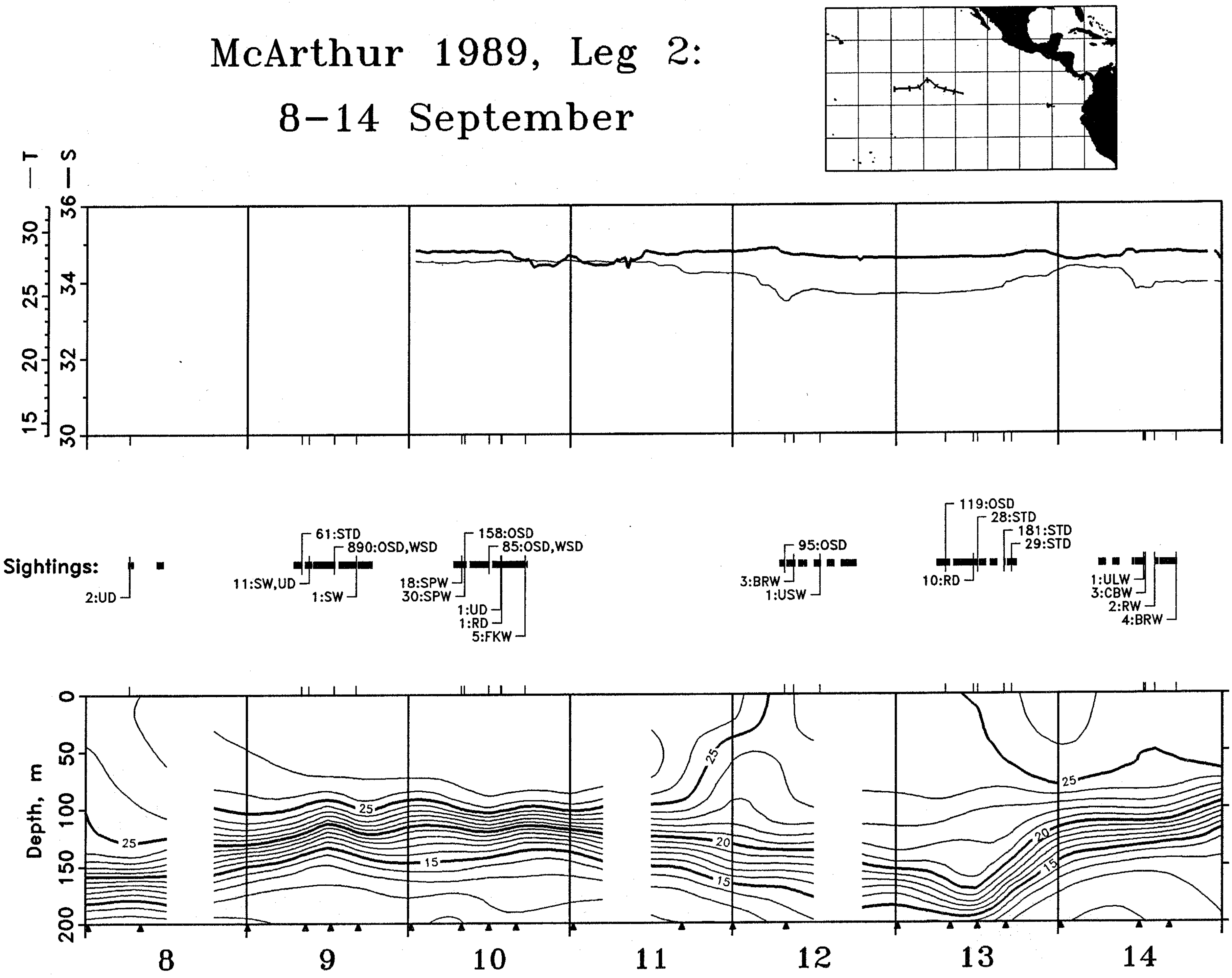


McArthur 1989, Leg 2:
1–7 September

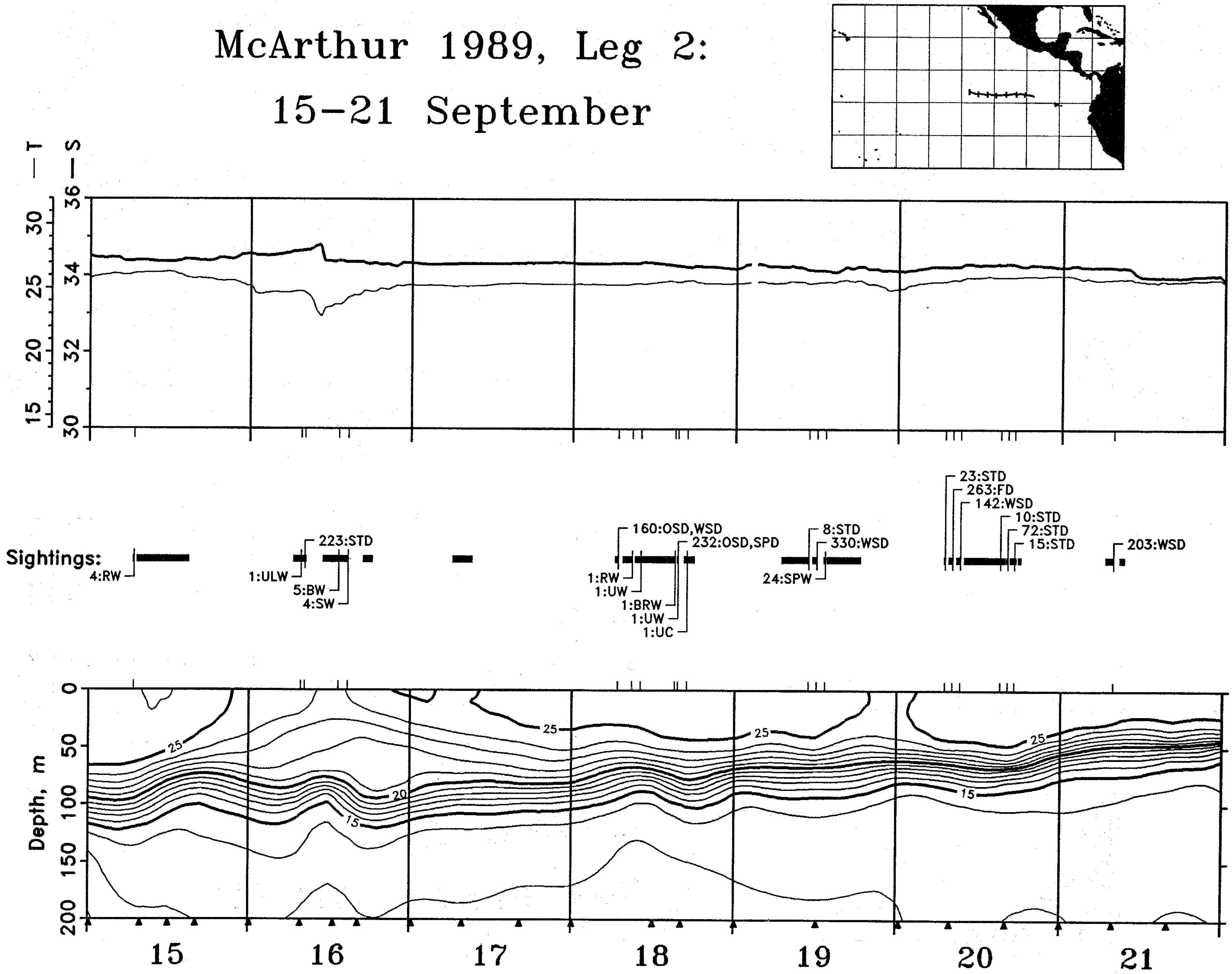




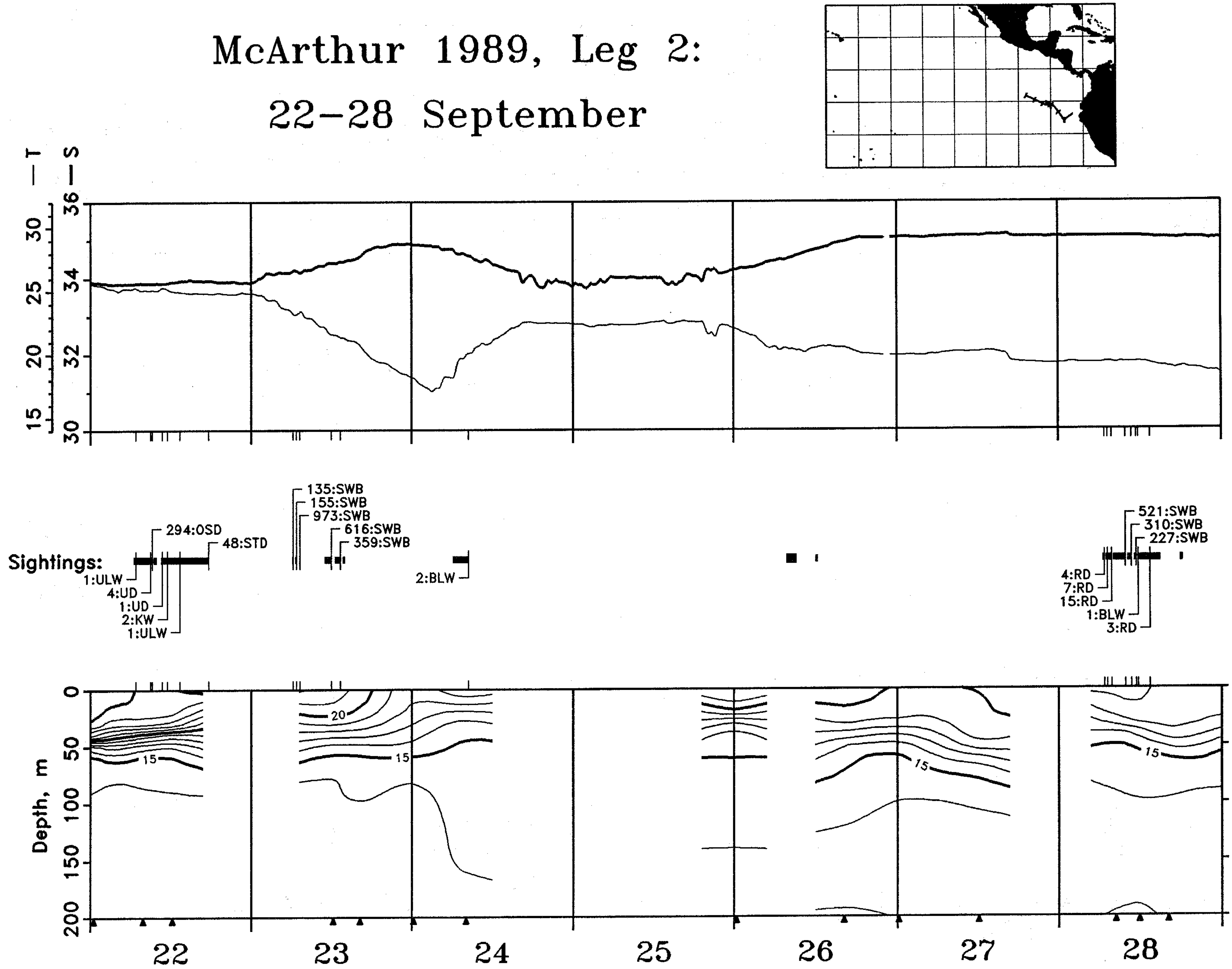
McArthur 1989, Leg 2:
8–14 September



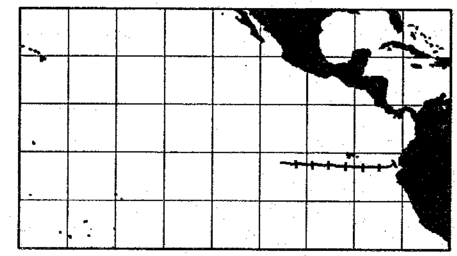
McArthur 1989, Leg 2:
15–21 September

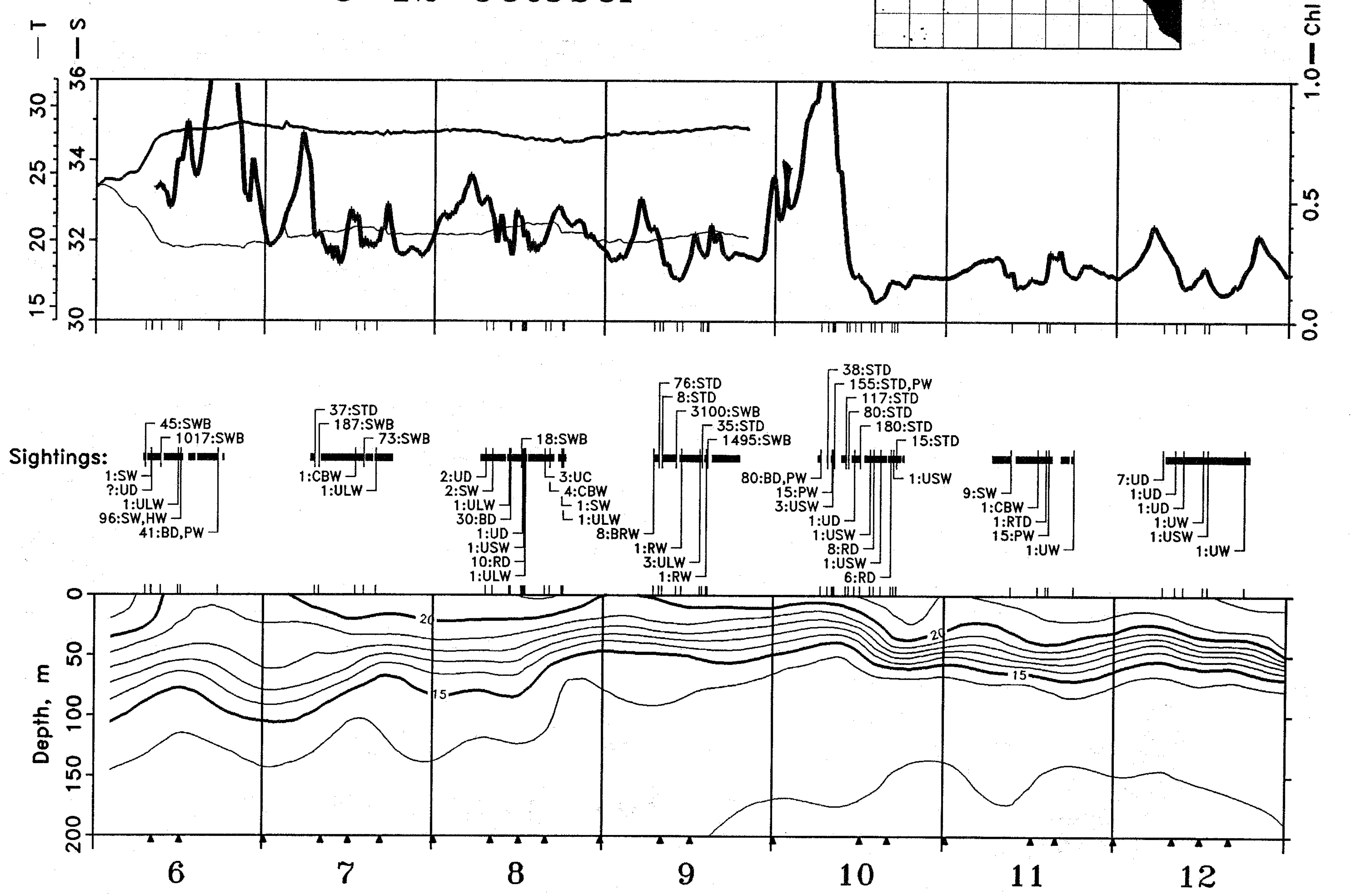


McArthur 1989, Leg 2:
22–28 September

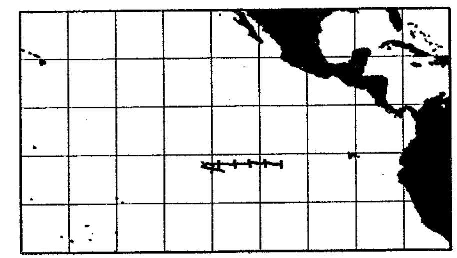


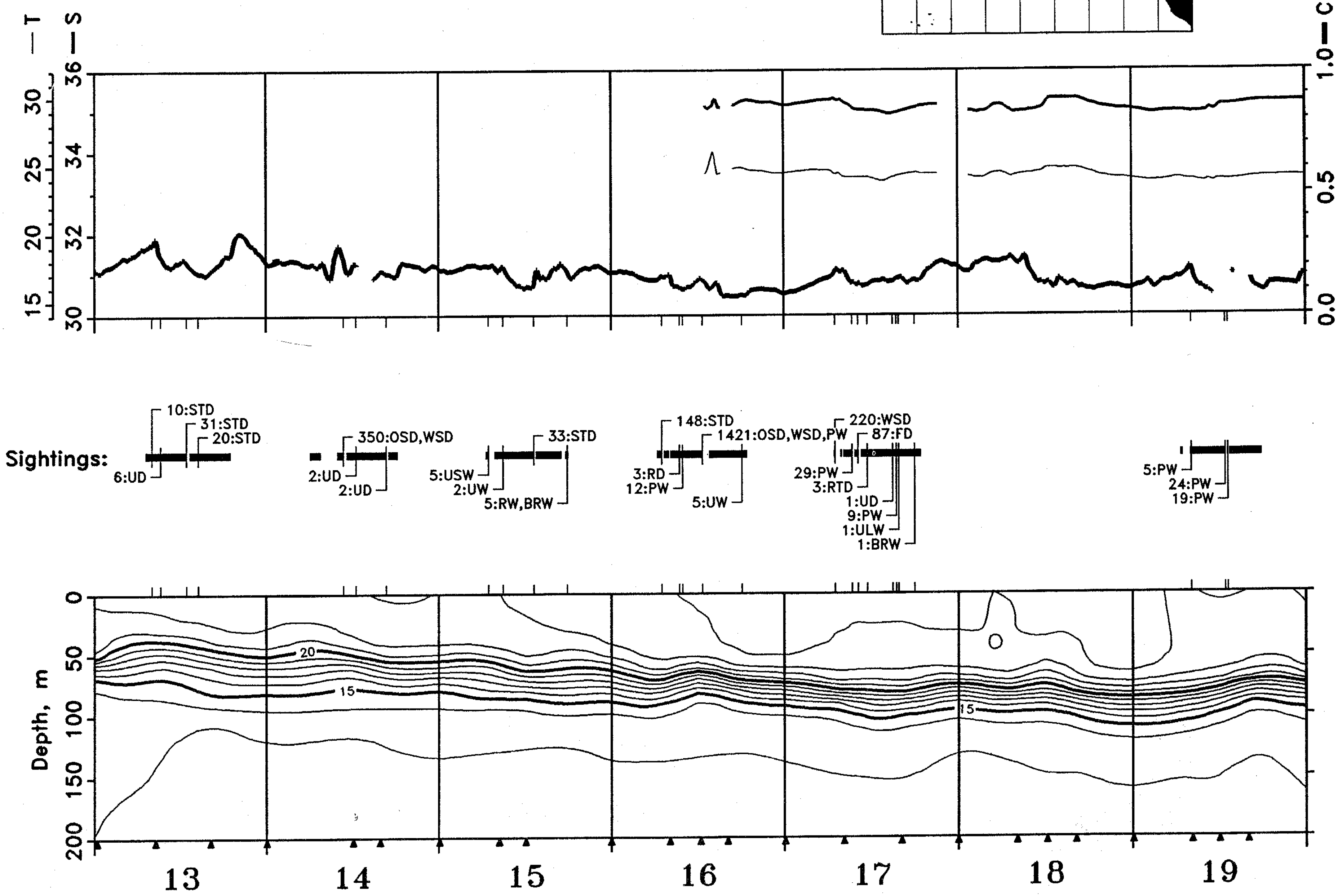
McArthur 1989, Leg 3:
6–12 October



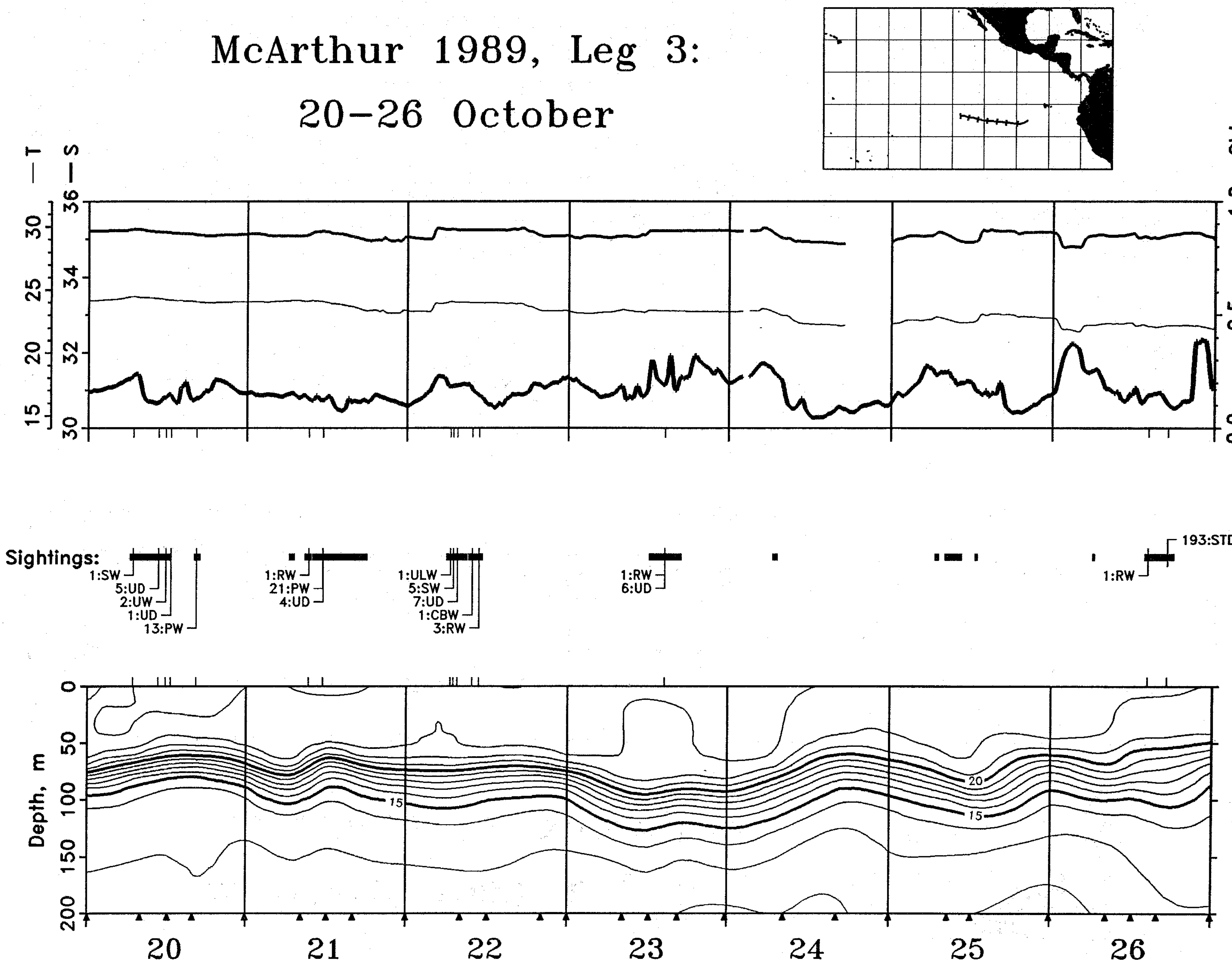


McArthur 1989, Leg 3: 13–19 October

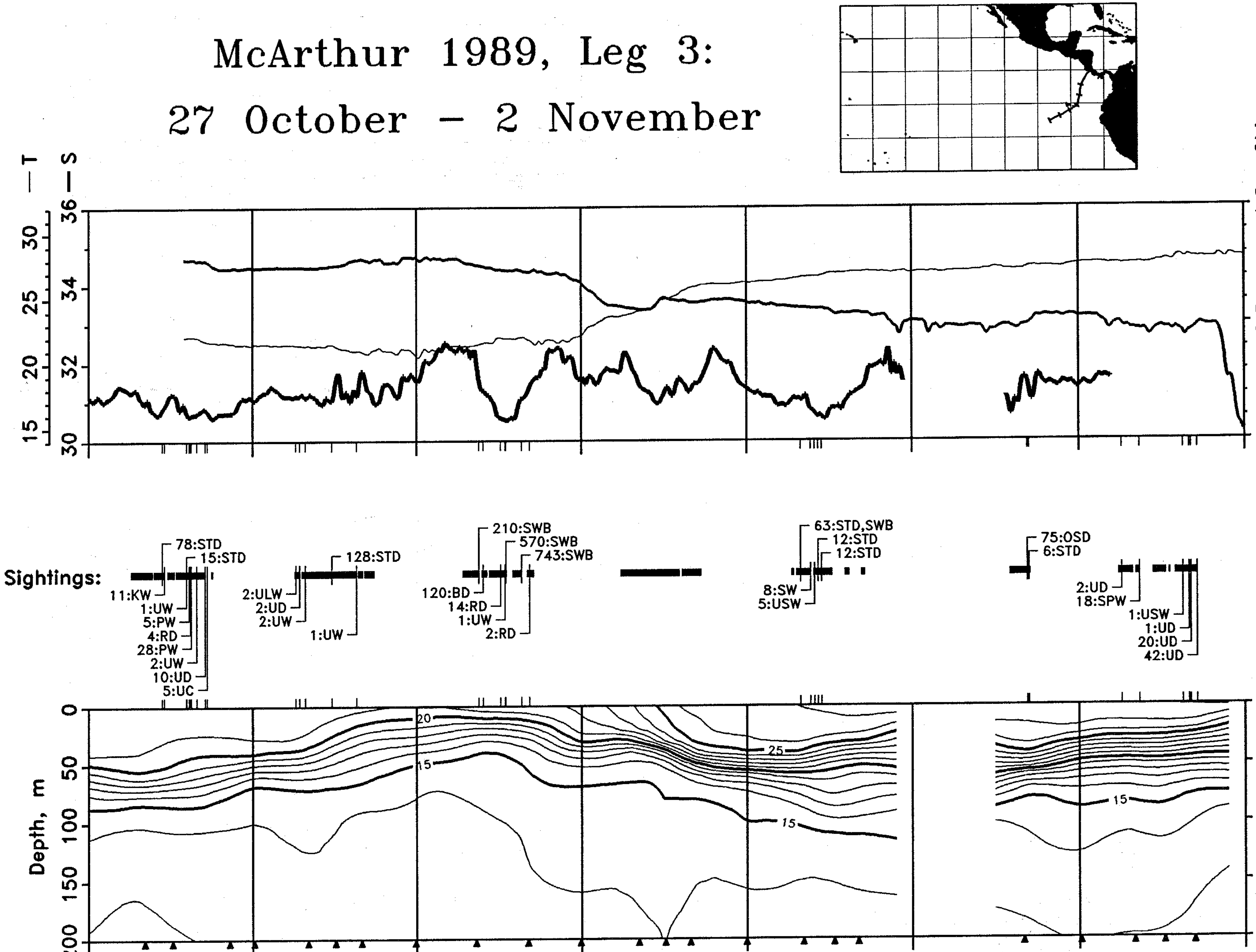




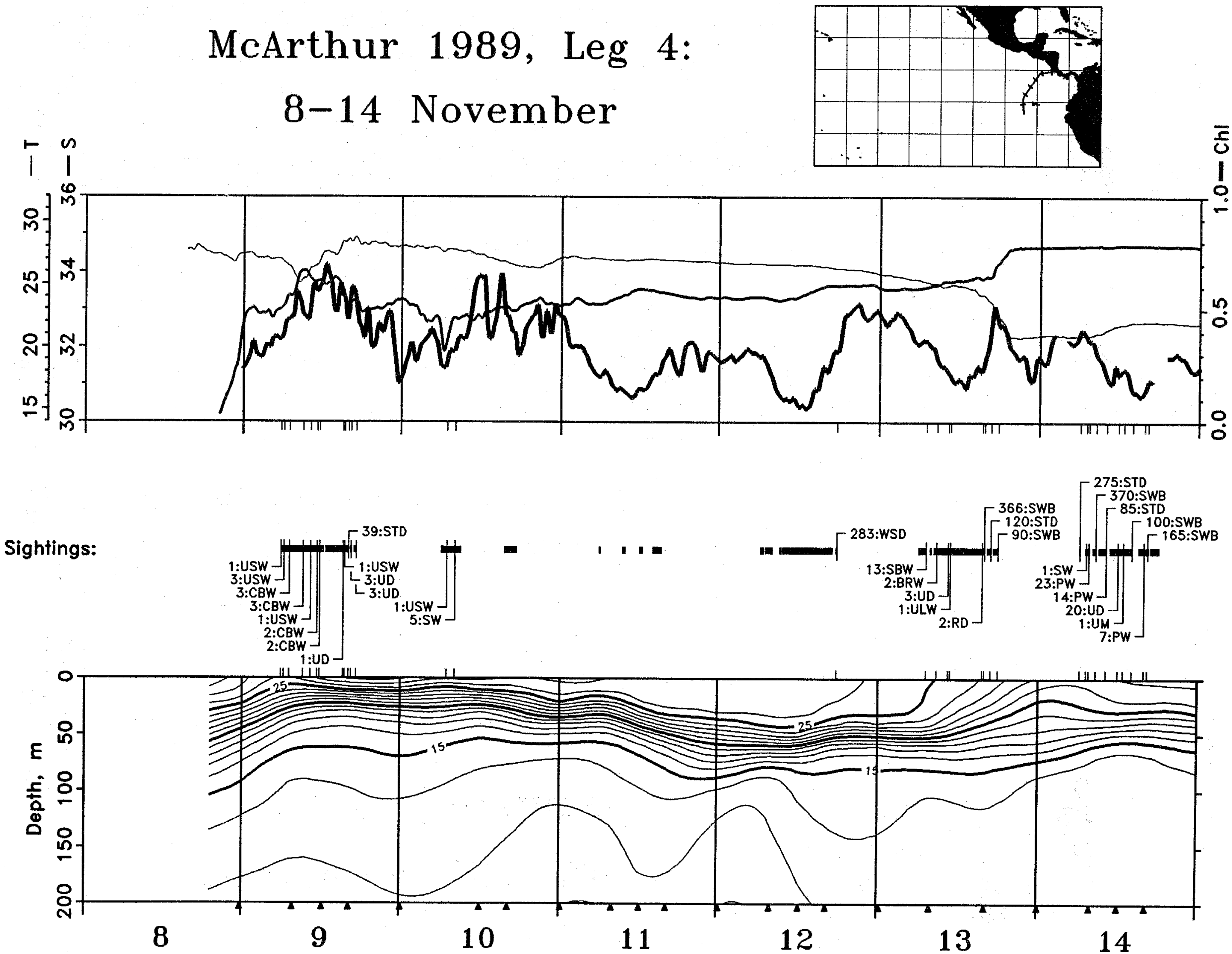
McArthur 1989, Leg 3:
20–26 October



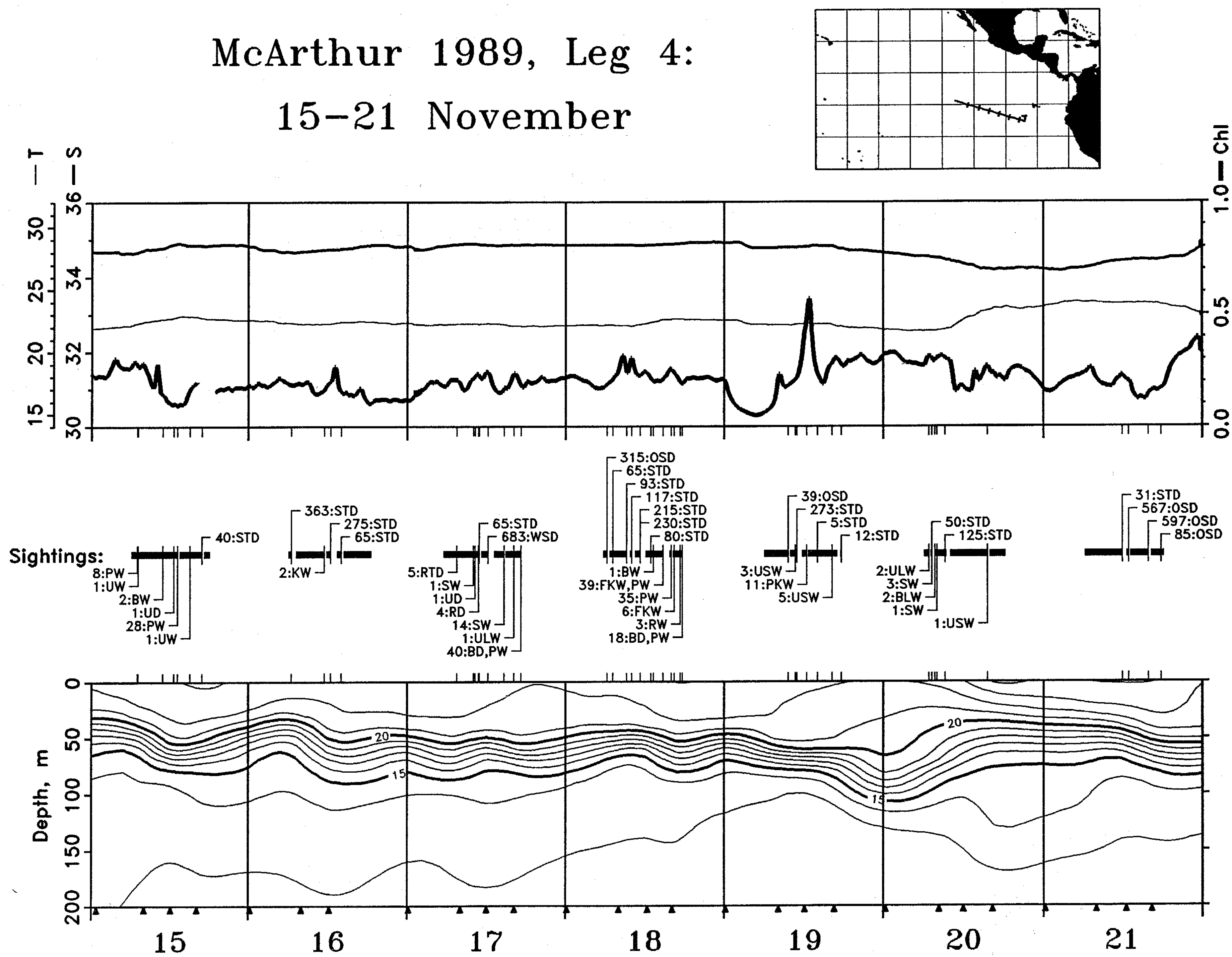
McArthur 1989, Leg 3:
27 October – 2 November



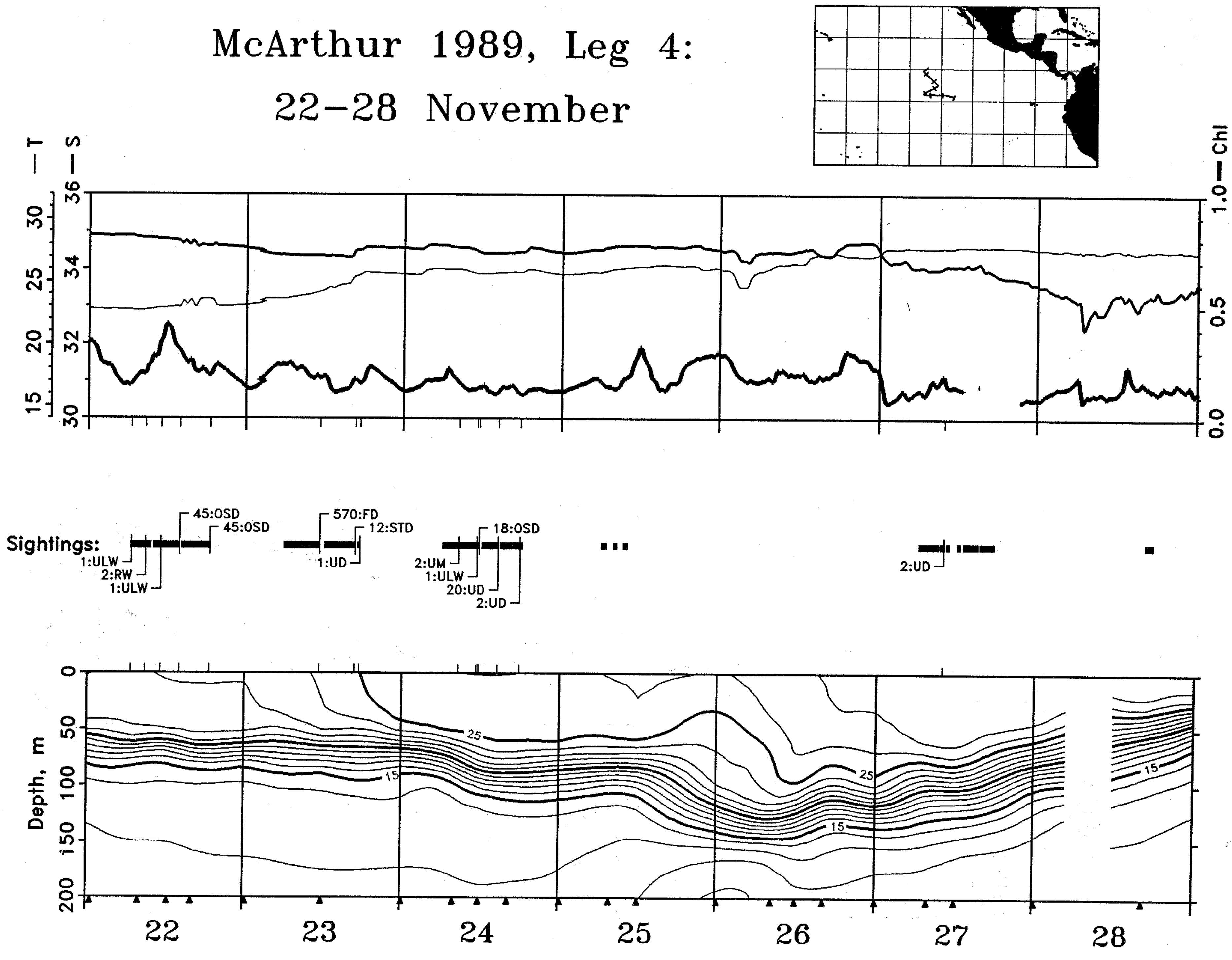
McArthur 1989, Leg 4: 8–14 November



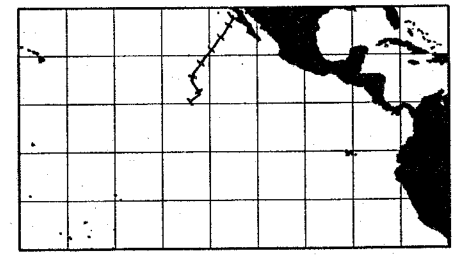
McArthur 1989, Leg 4:
15–21 November

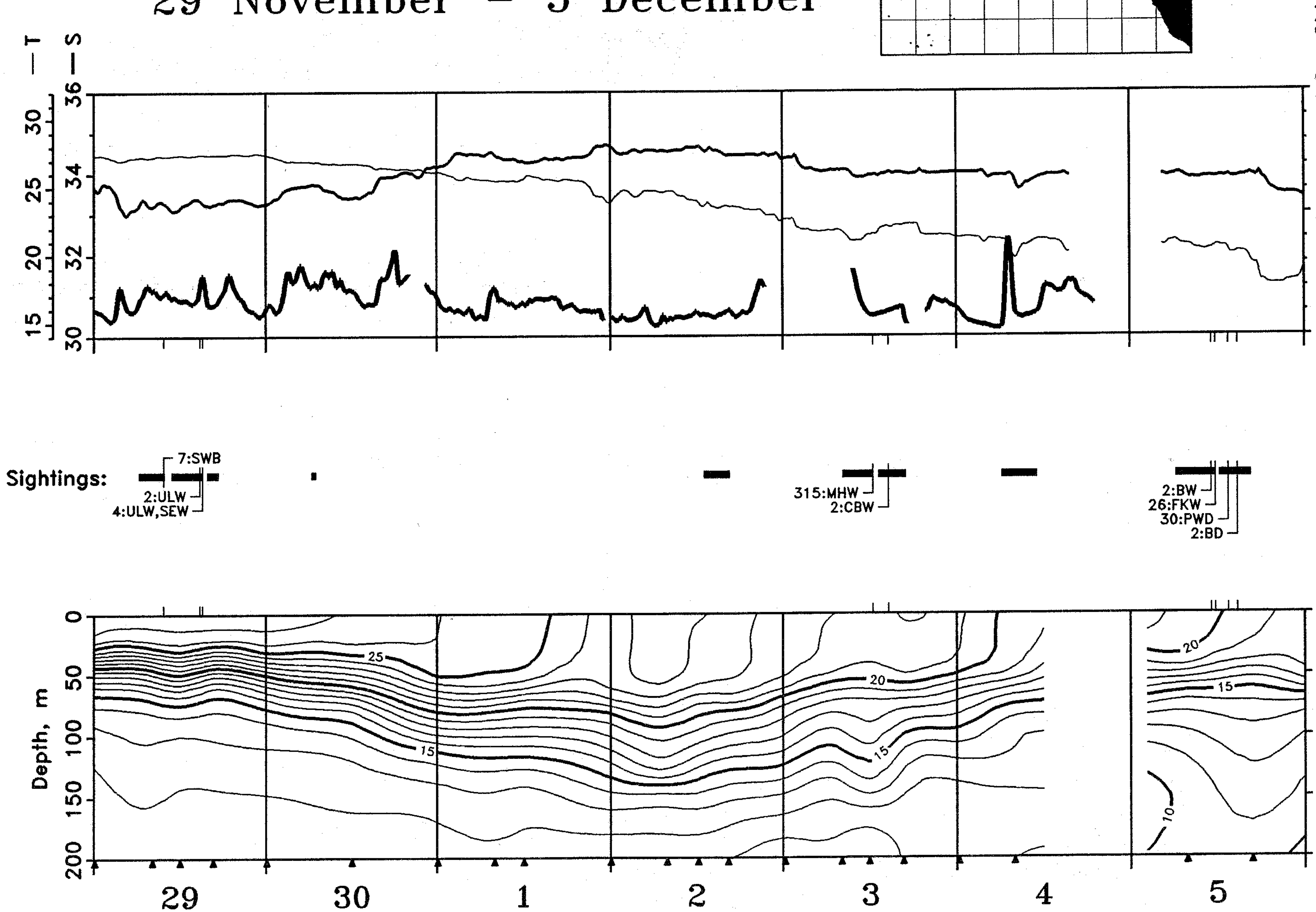


McArthur 1989, Leg 4:
22–28 November



McArthur 1989, Leg 4:
29 November – 5 December





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