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**BEARING STAKE EXERCISE:  
SOUND SPEED AND OTHER  
ENVIRONMENTAL VARIABILITY (U)**

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**DON F. FENNER  
WILLIAM J. CRONIN, JR.**

Ocean Acoustics Division  
Naval Oceanographic Laboratory

September 1978

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Prepared for  
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**FOREWORD**

(C) The BEARING STAKE Exercise was conducted by the Naval Ocean Systems Center (NOSC) under the sponsorship of the Naval Electronic Systems Command (PME-124) at five sites in the northwest Indian Ocean between January and April 1977. Personnel from the Naval Ocean Research and Development Activity (NORDA) managed the environmental data collection program and analyzed most resulting oceanographic, meteorological, and bathymetric data. This report defines the diverse sound speed variability at each exercise site and relates this variability to the distribution of various intrusive water masses, particularly high salinity Red Sea Intermediate Water. In addition, possible effects of the environment on acoustic propagation are assessed for each exercise site. This document presents the final environmental data analysis scheduled in support of BEARING STAKE acoustics.



**DR. RALPH GOODMAN  
TECHNICAL DIRECTOR  
NORDA**

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EXECUTIVE SUMMARY

(C) This report contains an interpretation of oceanographic (sound speed), meteorological, and bathymetric data collected during January through April 1977 as part of the BEARING STAKE Exercise at the following sites in the northwest Indian Ocean: site 1A/1B (Gulf of Oman), sites 2 and 3 (central Arabian Sea), site 4 (western Somali Basin), and site 5 (southern Arabian Sea).

ENVIRONMENTAL FINDINGS

- (U) The entire exercise took place during either the northeast monsoon (sites 1A, 1B, and 3 in January-February) or during the transitional period between the northeast and southwest monsoons (sites 4, 5, and 2 in March-April).
- (U) Representative exercise and southwest monsoon (June-September) sound speed profiles were quite similar except above a depth of 400-500 m (due to the effects of monsoonal reversal) and in regions where summer upwelling is expected (sites 2 and 4).
- (U) Overall, temporal and spatial sound speed variability was least at sites 2 and 3, intermediate at sites 1A/1B and 5, and greatest at site 4.
- (U) Sound speed profiles at site 1B were up to 5 m/sec lower than those at site 1A measured nearly one month earlier. This anomaly probably was caused by increased northeast monsoon upwelling after the site 1A occupation.
- (C) At site 4 and throughout the western Somali Basin, interleaving of four intrusive water masses (particularly high salinity Red Sea Intermediate Water and low salinity Antarctic Intermediate Water) caused complex and highly variable sound speed structures to depths in excess of 1800 m.

ACOUSTIC IMPLICATIONS

- (C) At all sites, the maximum temporal and spatial sound speed variability in the water column occurred between about 100 and 150 m, at or just below the tow depth of the low frequency CW source (generally 91 m).
- (C) At all sites except site 4, acoustic propagation was bottom-limited in respect to both the high frequency (generally 18-m) and low frequency (generally 91-m) CW sources.
- (C) Site 4 was effectively bottom-limited in respect to the high frequency (18-m) source. However, for the low frequency (91-m) source, at least 200 m of depth excess was found both at the site and along most acoustic tracks radial to the site.
- (C) The intense sound speed variability and microstructure found at site 4 and throughout the western Somali Basin should cause some propagation anomalies, particularly for the low frequency (91-m) source when some depth excess was present.
- (C) At all sites, ambient noise levels above 200 Hz should be moderate to low because of the low wind speeds and sea heights throughout the exercise.

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**ACKNOWLEDGEMENTS**

(U) The authors acknowledge the excellent performance of all field personnel involved in the collection of environmental data, and particularly thank the Naval Oceanographic Office personnel who collected deep ocean station data aboard USNS KINGSPOINT (T-AG-164) and USNS WILKES (T-AGS-23). Without this data, the analyses contained in this report would not have been possible. Grateful thanks are extended to the many members of NORDA involved in the preparation of this report. Ruben Busch analyzed all the bathymetric data used herein. Roger VanWyckhouse provided guidance to the authors in all stages of data reduction and edited this and other versions of the final report. Illustrations were prepared by Ruth Collins. This manuscript was typed by Mavis Coley and Susie Lee.

(U) Special acknowledgements are given to Dr. Robert R. Gardner of NOSC (BEARING STAKE Technical Director) and to Dr. Aubrey L. Anderson of NORDA (Head of the BEARING STAKE Acoustic Assessment Panel) for staunchly supporting a rigorous program of environmental data analysis. Special thanks are extended to Kenneth W. Lackie of the NORDA Liaison Office who originally planned the environmental data collection portion of the exercise.

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**BEARING STAKE EXERCISE:  
SOUND SPEED AND OTHER ENVIRONMENTAL VARIABILITY (U)**

**I. (U) INTRODUCTION**

(C) During January through April 1977, the BEARING STAKE exercise was conducted by the Naval Ocean Systems Center (NOSC) under the sponsorship of the Naval Electronics Systems Command (PME-124) at five sites throughout the northwest Indian Ocean. The Environmental Effects Branch, Ocean Acoustics Division of NORDA had primary responsibility for analyzing environmental (oceanographic, bathymetric, and meteorological) and navigational data to support exercise acoustic data analysis. This report represents the final environmental data analysis in support of BEARING STAKE. Much of the work contained herein has appeared previously in the BEARING STAKE Acoustic Assessment Report (NOSC, 1978).

(C) Figure 1 shows the location of the five major acoustic sites and the sound speed analyses contained in the main body of this report. Other sound speed analyses performed by NORDA for NOSC are indexed on Figure 21 and presented in Appendix A. Environmental data were collected at one or more sites by the following vessels:

- USNS KINGSPORT (T-AG-164) (KP)
- USNS MYER (T-ARC-6) (MY)
- USNS WILKES (I-AGS-23) (WI)
- USNS MIZAR (T-AGOR-11) (MZ)
- HMAS DIAMANTINA (DI)

The two-letter abbreviations in parentheses following each of the above vessels are the same as used in various illustrations of this report. Environmental data collection periods at each site were as follows:

- Site 1A: 14-24 January
- Site 3: 1-16 February
- Site 1B: 16-26 February
- Site 4: 9-26 March
- Site 5: 8-21 April
- Site 2: 21-30 April

All sites were occupied either during the northeast monsoon (December through February) or during the transitional period between the northeast and southwest monsoons (March through May). Site 1 was occupied twice, denoted by sites 1A and 1B.

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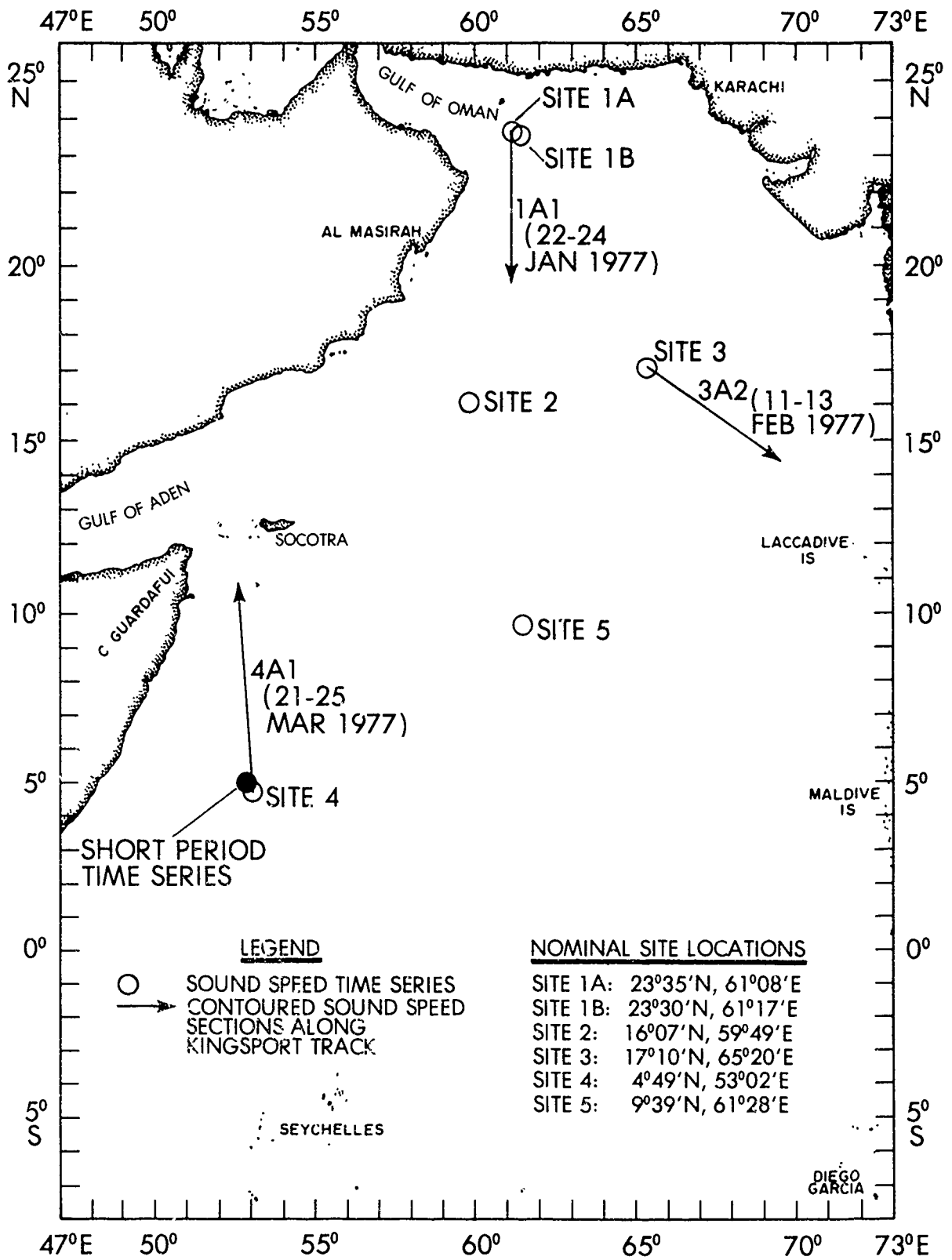


Figure 1.(C) Location of exercise sites and sound speed analyses (U)

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**II. (U) GENERAL DISCUSSION OF ENVIRONMENTAL DATA**

(U) Table 1 summarizes oceanographic and meteorological data collected at each major acoustic site. Oceanographic data consisted of expendable bathythermograph (XBT) observations and sound velocity/salinity-temperature-depth (SV/STD) stations. XBTs are summarized by the maximum depth to which each trace was acceptable. Meteorological data included observations of wind speed, wind direction, sea height, and swell height. In addition to those data listed in Table 1, sea surface temperature observations were collected continuously by WILKES at sites 1A, 1B, 3, and 4, and bathymetric data were collected by KINGSPORT, WILKES, and MIZAR throughout the exercise area. NORDA provided NOSC with analyzed bathymetric data along KINGSPORT acoustic tracks, while NOSC analyzed that WILKES and MIZAR data necessary for acoustic assessment. All bathymetric data analyzed by NORDA were corrected for the speed of sound in seawater using the tables of Matthews (1939).

(U) Three types of XBTs were deployed during the exercise: Sippican Model T-5 probes (maximum depth of 1830 m) by KINGSPORT, MYER, WILKES, and MIZAR; Model T-7 probes (maximum depth of 760 m) by MIZAR and DIAMANTINA; and Model T-4 probes (maximum depth of 460 m) by DIAMANTINA. The great majority of the MIZAR XBTs were T-7 probes; the great majority of the DIAMANTINA XBTs were T-4 probes. All XBT traces were machine digitized and converted to sound speed using the equation of Wilson (1960). Salinities necessary for sound speed calculation were individually assigned to each XBT trace, and were based on a salinity field derived from exercise SV/STD data and historical north-east monsoon Nansen cast data. Approximately 45% of the T-5 probes deployed failed at depths less than 1500 m due to wire entanglement, wire rubbing, or actual wire breakage. Fortunately, it was possible to determine deep sound channel (DSC) statistics throughout the exercise area from exercise SV/STDs and those T-5 XBTs that reached their maximum depth.

(U) All three XBT models measure temperature to  $\pm 0.2^{\circ}\text{C}$ , which results in a calculated sound speed accuracy of about  $\pm 0.8$  m/sec assuming that there are no errors in Wilson's equation. The SV/STD systems used by KINGSPORT, WILKES, and MIZAR measure sound speeds with a precision of about  $\pm 0.3$  m/sec, and yield Wilson equation sound speeds accurate to about  $\pm 0.1$  m/sec. Generally, BEARING STAKE sound speeds calculated from XBT temperatures were up to 1.0 m/sec higher than those measured directly and up to 0.5 m/sec higher than those calculated from SV/STD temperatures and salinities. Most of this error is attributable to XBT inaccuracies compounded by inaccuracies in Wilson's equation (Carnvale, et al., 1968; MacKenzie, 1971). Despite these inaccuracies, the total exercise sound speed data base (XBTs plus SV/STDs) is adequate for propagation loss calculations since measured and calculated sound speed gradients were nearly identical throughout the upper 2000-2500 m of the water column. Below 3000 m, Wilson equation sound speeds were up to 2.0 m/sec higher than those measured directly. Therefore, sound speeds measured during the exercise were used to extend profiles so as not to bias propagation loss calculations.

(U) Measured sound speeds also were used in calculating critical depth and 90-m conjugate depth. Critical depth, the depth where the maximum sound speed at the surface or in the near-surface layer (i.e., sonic layer depth) recurs, defines the bottom of the DSC. The DSC axis is the depth of the absolute sound speed minimum in the water column. The depth where the sound speed at 90 m recurs is defined as 90-m conjugate depth, and delineates the minimum depth necessary for refraction of downward rays from a 90-m source. Because sound speeds calculated from Wilson's equation were up to 1.0 m/sec higher than those measured directly, critical and 90-m depths based on calculated deep gradients could be up to 70 m shallower than those based on measured deep sound speed gradients. Consequently, measured sound speeds for depths greater than 3000 m rather than computed values were used to determine critical and 90-m conjugate depths.

(U) As previously reported (NOSC, 1977), a substantial percentage of data from BEARING STAKE XBTs initially appeared too warm below a depth of 600-1000 m when compared to exercise SV/STD data. Preliminary evaluation of the XBT traces indicated that these erroneously warm temperatures were caused mainly by an alteration in the sink rate of the XBT probes due to entanglement with towed projectors and/or wire rubbing. However, during later analysis of the traces, XBT recorder malfunctions (caused primarily by a slow recorder servo-motor response) were uncovered that could lead to warmer temperatures in that region of the water column where temperature becomes basically isothermal (i.e., below about 1000 m). These errors were compensated during machine digitization of the traces, so that most XBT

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TABLE 1 (U)  
SUMMARY OF BEARING STAKE OCEANOGRAPHIC DATA (U)

| SHIP         | XBTs      |                |           | SV/STDs   | WFATHER OBS |
|--------------|-----------|----------------|-----------|-----------|-------------|
|              | 100-600 m | 600-1500 m     | >1500 m   |           |             |
|              |           | <u>Site 1A</u> |           |           |             |
| KINGSPORT    | 4         | 9              | 24        | 4         | 132         |
| MYER         | 4         | 4              | 9         | 0         | 204         |
| WILKES       | 1         | 0              | 1         | 5         | 0           |
| Total        | <u>9</u>  | <u>13</u>      | <u>34</u> | <u>9</u>  | <u>336</u>  |
|              |           | <u>Site 1B</u> |           |           |             |
| KINGSPORT    | 10        | 1              | 1         | 12        | 84          |
| MYER         | 0         | 4              | 8         | 0         | 158         |
| WILKES       | 3         | 4              | 13        | 5         | 0           |
| MIZAR        | 7         | 6              | 6         | 2         | 96          |
| DIAMANTINA   | 20        | 0              | 0         | 0         | 13          |
| Total        | <u>40</u> | <u>15</u>      | <u>28</u> | <u>19</u> | <u>351</u>  |
| Site 1 Total | 49        | 28             | 62        | 28        | 687         |
|              |           | <u>Site 3</u>  |           |           |             |
| KINGSPORT    | 4         | 7              | 21        | 12        | 168         |
| MYER         | 3         | 2              | 13        | 0         | 321         |
| WILKES       | 9         | 12             | 36        | 6         | 0           |
| MIZAR        | 20        | 10             | 2         | 5         | 96          |
| DIAMANTINA   | 12        | 0              | 0         | 0         | 13          |
| Total        | <u>48</u> | <u>31</u>      | <u>72</u> | <u>23</u> | <u>598</u>  |
|              |           | <u>Site 4</u>  |           |           |             |
| KINGSPORT    | 2         | 25             | 25        | 13        | 288         |
| MYER         | 0         | 4              | 14        | 0         | 332         |
| WILKES       | 13        | 20             | 36        | 4         | 0           |
| MIZAR        | 6         | 18             | 4         | 3         | 264         |
| DIAMANTINA   | 32        | 8              | 0         | 0         | 44          |
| Total        | <u>53</u> | <u>75</u>      | <u>79</u> | <u>20</u> | <u>928</u>  |
|              |           | <u>Site 5</u>  |           |           |             |
| KINGSPORT    | 2         | 16             | 4         | 4         | 132         |
| MYER         | 2         | 11             | 3         | 0         | 253         |
| MIZAR        | 2         | 14             | 0         | 3         | 156         |
| DIAMANTINA   | 21        | 4              | 0         | 0         | 29          |
| Total        | <u>27</u> | <u>45</u>      | <u>7</u>  | <u>7</u>  | <u>570</u>  |
|              |           | <u>Site 2</u>  |           |           |             |
| KINGSPORT    | 1         | 10             | 0         | 1         | 108         |
| MYER         | 1         | 3              | 9         | 0         | 192         |
| MIZAR        | 9         | 10             | 1         | 1         | 156         |
| DIAMANTINA   | 0         | 0              | 0         | 0         | 25          |
| Total        | <u>11</u> | <u>23</u>      | <u>10</u> | <u>2</u>  | <u>481</u>  |
| Grand Total  | 188       | 202            | 230       | 80        | 3264        |

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temperatures below about 1000 m agreed to 0.1°-0.2°C with those measured using SV/STDs, well within the accuracy of the XBT system.

### III. (U) GENERAL OCEANOGRAPHIC SETTING

(C) The sound speed structure of the northwest Indian Ocean has been extensively discussed by Fenner and Bucca (1972a and b) and more recently by Colborn (1976). The following paragraphs review these previous works tailored to the five BEARING STAKE acoustic sites.

(U) Sound speed profiles throughout the exercise area were influenced by one or more of the following intrusive water masses:

- High salinity Persian Gulf Intermediate Water (PGIW) with a core at 250-400 m
- Low salinity Subtropical Subsurface Water (SSW) at 400-500 m
- High salinity Red Sea Intermediate Water (RSIW) at 500-900 m
- Low salinity Antarctic Intermediate Water (AAIW) at 700-800 m
- Low salinity Banda Intermediate Water (BIW) at 900-1000 m

These various water masses can perturb the negative sound speed gradient lying between the permanent thermocline (100-200 m) and the DSC axis. Generally, low salinity cores result in sound speed minima, high salinity cores in sound speed maxima. During BEARING STAKE, sound speed maxima and minima frequently appeared as microstructure with a limited depth extent, particularly in the presence of several intrusive water masses. Figure 2 gives the temperature-salinity (T-S) indices for each of the five intrusive water masses and is taken directly from Fenner and Bucca (1972b).

(U) Sites 1A and 1B both were influenced by high salinity PGIW that emanates from the Persian Gulf through the Straits of Hormuz. In the Gulf of Oman, this water mass frequently causes sound speed maxima at depths of 200-250 m, just below the base of the permanent thermocline. Both sites also were affected by highly variable northeast monsoon upwelling that occurs at the northern end of the Arabian Sea (Cushing, 1971). SSW may have been present at sites 1A/1B, but is not detectable by a salinity minimum in the Gulf of Oman, rather only by an oxygen minimum.

(U) Site 2, located just east of the mouth of the Gulf of Aden, was influenced by PGIW and RSIW. The latter water mass emanates from the Red Sea into the Gulf of Aden and then into the Arabian Sea. At site 2, PGIW and RSIW actively intermix with low salinity SSW and subsequently sink within the upper 1000 m of the water column. Such intermixing can produce extensive microstructure. In contrast, minimal oceanographic activity occurred at site 3. At this site, PGIW is too diluted to affect sound speed structures and RSIW is barely detectable in historical sound speed profiles. None of the three low salinity intrusive water masses generally is present at site 3.

(U) Site 4 was located astride a primary flow of RSIW that extends south along the east African coast at depths of 600-900 m. This site was strongly influenced by low salinity SSW and AAIW that flow north along the east African coast between about 400 and 800 m. These two low salinity flows lie above and below the core of high salinity RSIW and intensively intermix with RSIW throughout the Somali Basin (Warren, et al., 1966), causing extensive sound speed microstructure. Site 4 also can be influenced by low salinity BIW that flows east across the Indian Ocean from the region of the Indonesian Archipelago (Rochford, 1966) and by high salinity PGIW that flows south along the Somalia coast. Generally, however, the latter two water masses, when present, cause insignificant amounts of sound speed microstructure in the vicinity of site 4. Since this site was occupied towards the end of the northeast monsoon, it was not influenced by the strong Somali Current that flows north along the east African coast during summer. Generally, the monsoon reversal does not take place in the Somali Basin until late April or early May (Duing and Schott, 1978), well after the site 4 occupation.

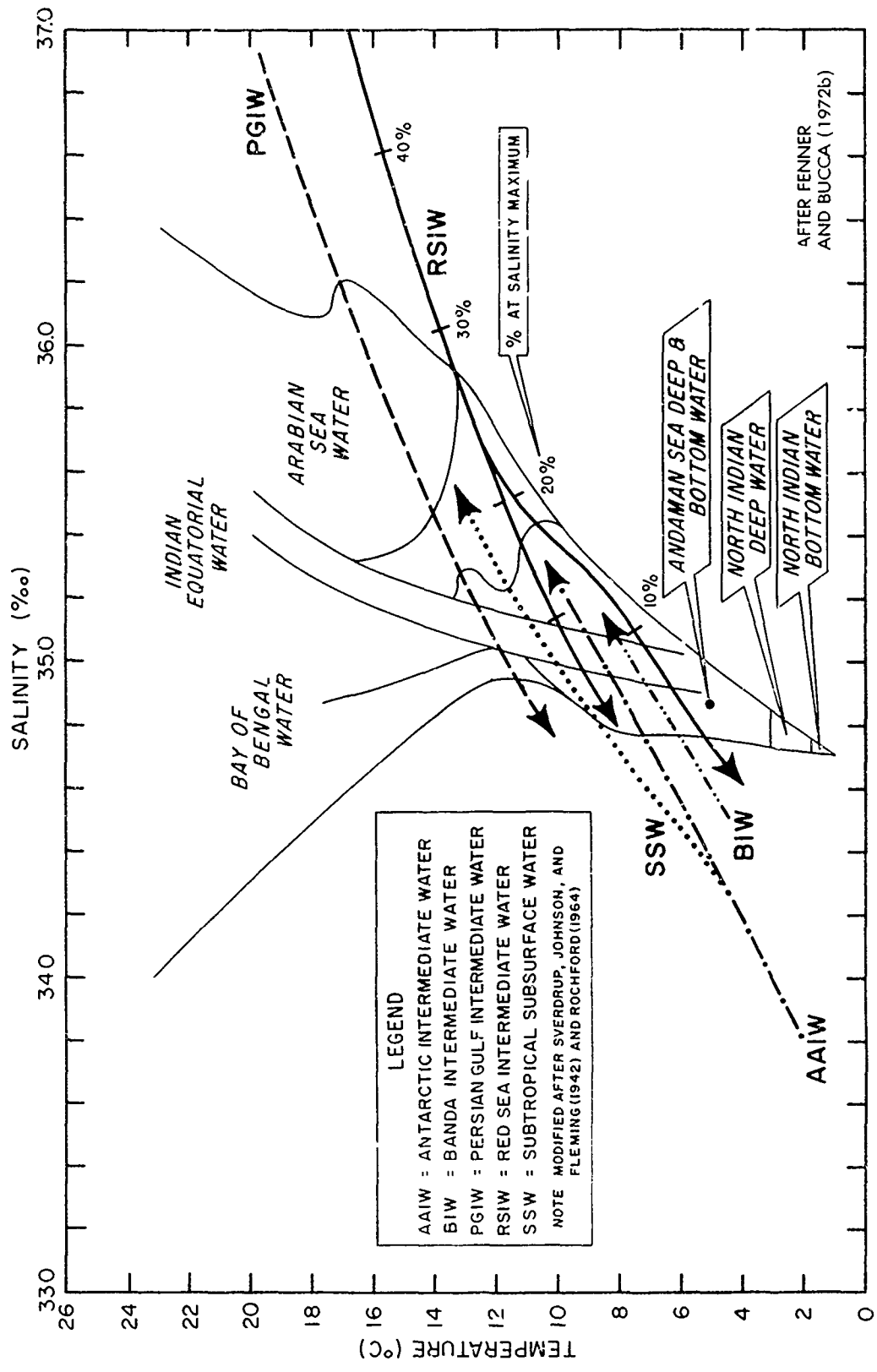


Figure 2.(U) Temperature-salinity relations in the North Indian Ocean (U)

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(U) Like site 4, site 5 also was located astride a preferential flow of RSIW and was influenced strongly by SSW. Due to its location just north of the Carlsberg Ridge, this site was not influenced by AAIW or BIW. PGIW was present at site 5, but did not markedly affect sound speed structures. Generally, effects of water masses on sound speeds at site 5 were less than that at site 4, but somewhat greater than that at sites 2 and 3 directly to the north.

### IV. (U) ENVIRONMENTAL VARIABILITY AT SITES 1A/1B

(C) Sites 1A and 1B were located in the eastern part of the Gulf of Oman within the Oman Basin. The Bottom Mounted Array (BMA) at site 1B was implanted within 5 nm (9 km) of that at site 1A, but nearly one month later. As previously mentioned, both sites were under the influence of PGIW with a high salinity core at 200-250 m and highly variable northeast monsoon upwelling. Figure 3 presents the site 1A environmental summary. Sound speed perturbations above 600 m shown in this figure were caused by PGIW that apparently was sinking at site 1A. A sonic layer 50-70 m deep was present at the site throughout most of the occupation. The exception was between 17 and 20 January when surface insolation masked the layer. During the 19-day occupation, the depth of the DSC oscillated between about 1600 and 1850 m with a sound speed variation at the axis of about 2.5 m/sec. Due to relatively high surface sound speeds and the shallow nature of the Gulf of Oman, site 1A was bottom-limited in respect to both the high frequency (24-m) and low frequency (91-m) CW sources. The greatest temporal sound speed variability in the water column (about 10 m/sec) occurred at 100 m, just below the nominal depth of the low frequency source. Meteorological conditions were relatively stable at site 1A, with wind speeds generally less than 10 m/sec, sea heights less than 2 m, and swell heights less than 3 m.

(C) The environmental summary for site 1B is given in Figure 4. Although PGIW was present at site 1B, it did not cause sound speed perturbations in the upper water column. A sonic layer was absent during most of the site 1B occupation, apparently due to surface insolation. The depth of the DSC varied between 1580 and 1820 m over nine days with a sound speed change of less than 2 m/sec. Like that at site 1A, acoustic propagation at site 1B was bottom-limited in respect to both the high (18-m) and low (102-m) frequency CW sources. The greatest temporal sound speed variability (about 10 m/sec) again occurred at 100 m, near the nominal depth of the low frequency source. Wind speed, sea height, and swell height gradually decreased during the site 1B occupation, but were less than 10 m/sec or 2 m throughout.

(C) At depths less than 1800 m, the envelope of temporal sound speed variability at site 1B (Figure 4) lay at lower sound speeds than that for site 1A (Figure 3), with a maximum difference of 4-5 m/sec at 400-m depth. The lowest sound speed profile in the Figure 4 envelope (KP SV/STD 26) represents conditions at the beginning of KINGSPORT event S1 at site 1B. Figure 5 compares sound speed and temperature profiles for KP SV/STD 26 with those taken nearly one month earlier at the beginning of KINGSPORT event S1 at site 1A. The 4- to 5-m/sec difference in sound speeds at 400 m is due to a drop in temperature of about 1.3°C. This change probably was caused by increased upwelling during February (site 1B occupation). Wind speeds and directions between 16 and 20 February (Figure 4) were far more persistent than those encountered at site 1A (Figure 3), a condition conducive to upwelling. Another possible cause for this phenomena is an incursion of cooler, lower salinity SSW into the Gulf of Oman after the site 1A occupation. However, as previously mentioned, SSW cannot be identified in the Gulf of Oman by a salinity minimum, but rather only by an oxygen minimum. Unfortunately, no oxygen data were collected during BEARING STAKE. Sound speed cross sections for KINGSPORT events S1 at site 1A and S1 at site 1B are presented in Appendix A as Figures 22 and 23, respectively, and have been discussed in the BEARING STAKE Acoustic Assessment Report (NOSC, 1978).

(C) Figure 6 shows a contoured sound speed cross section along the KINGSPORT 1A1 track, and Figure 7 shows an overplot of selected sound speed profiles along this same track. The track was planned to correspond with an aircraft SUS event flown between 220914Z and 221103Z January 1977. Unfortunately, the actual SUS run lay about 43 nm (80 km) east of the KINGSPORT track. A well defined sonic layer was present along the entire section at depths between 50 and 100 m. The DSC axis varied in depth between 1750 and 1930 m with a sound speed variation of about 2 m/sec. Both sonic layer and axial



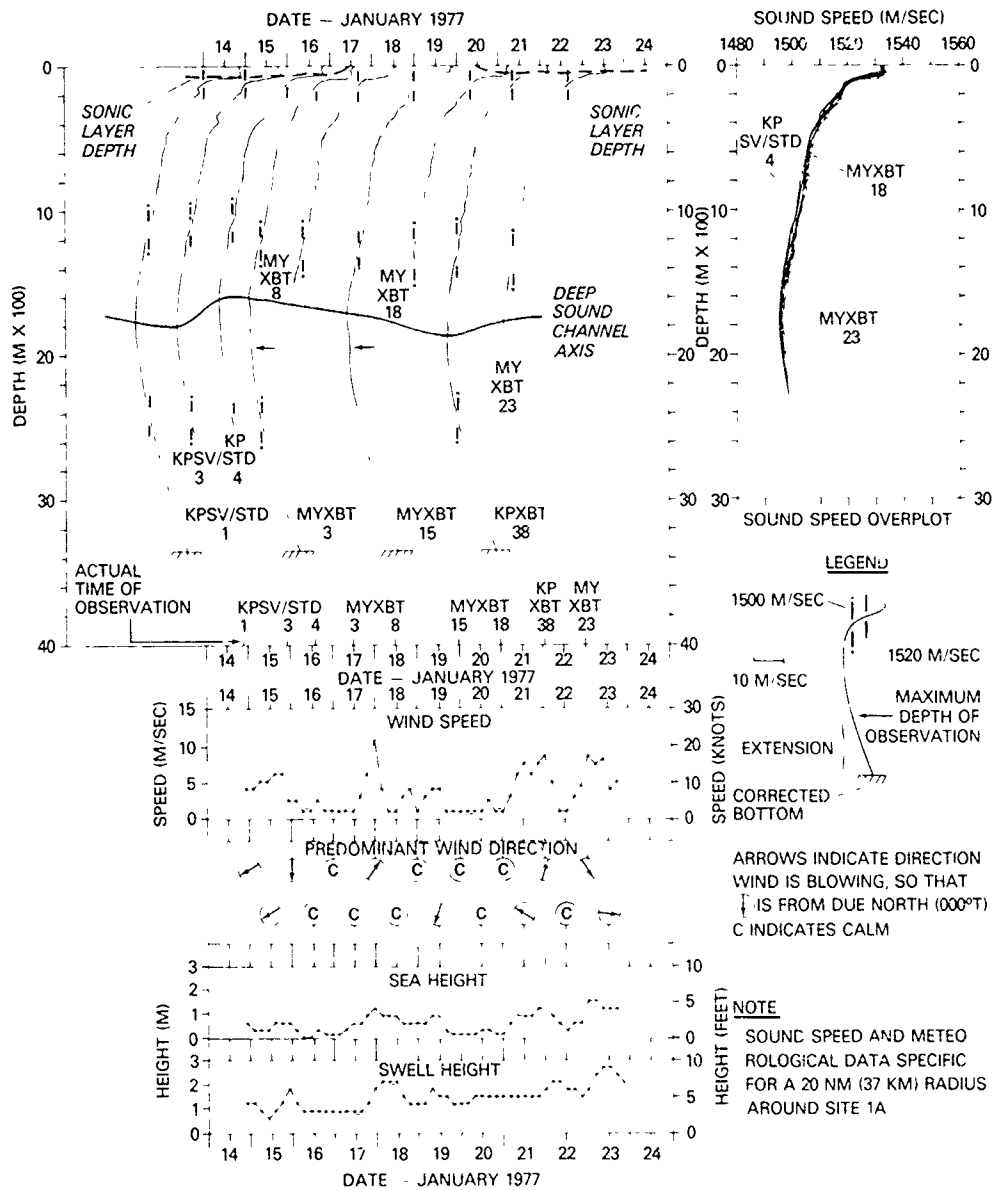


Figure 3.(U) Environmental summary at site 1A (14-24 January 1977) (U)

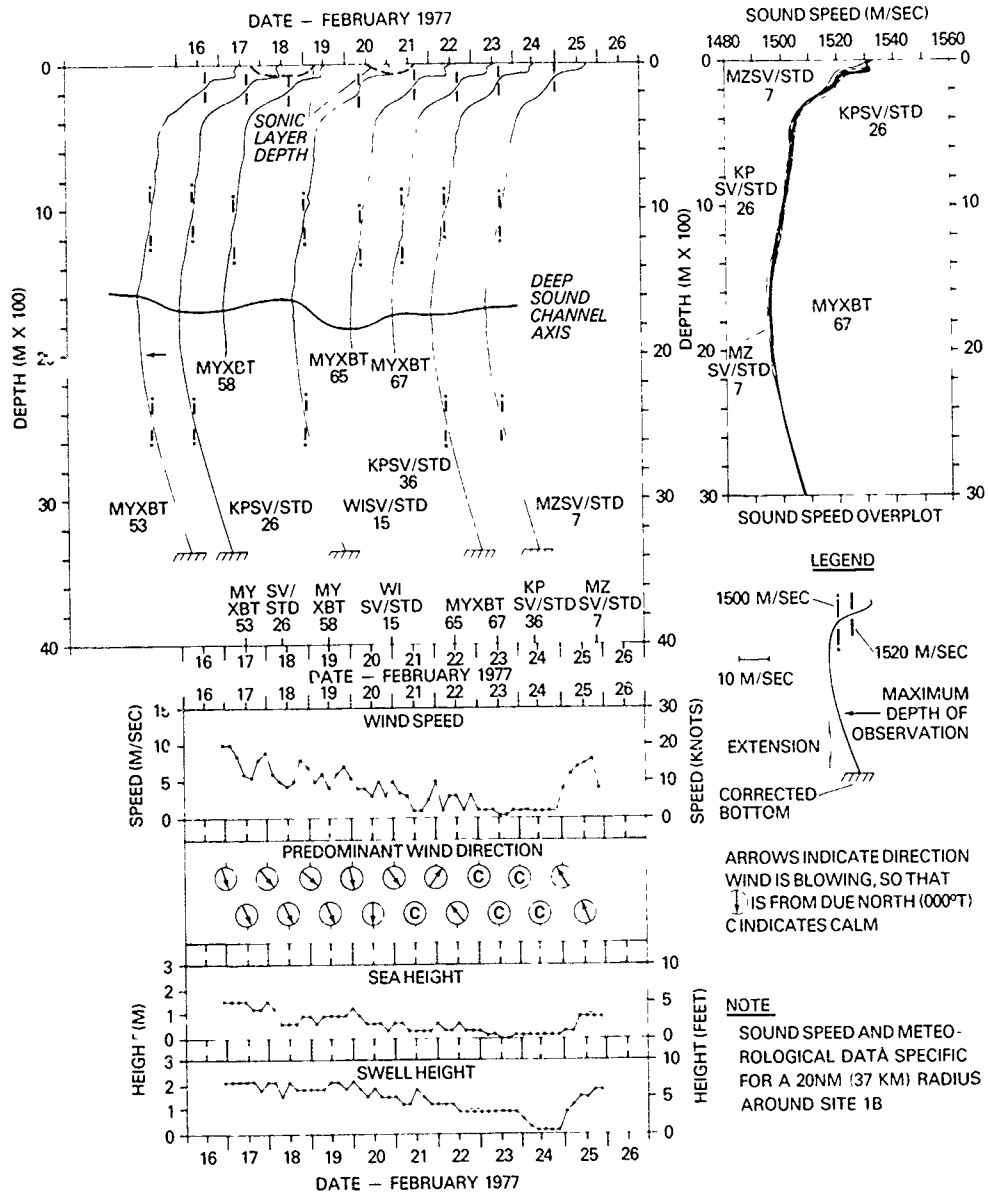


Figure 4.(U) Environmental summary at site 1B (16-26 February 1977) (U)

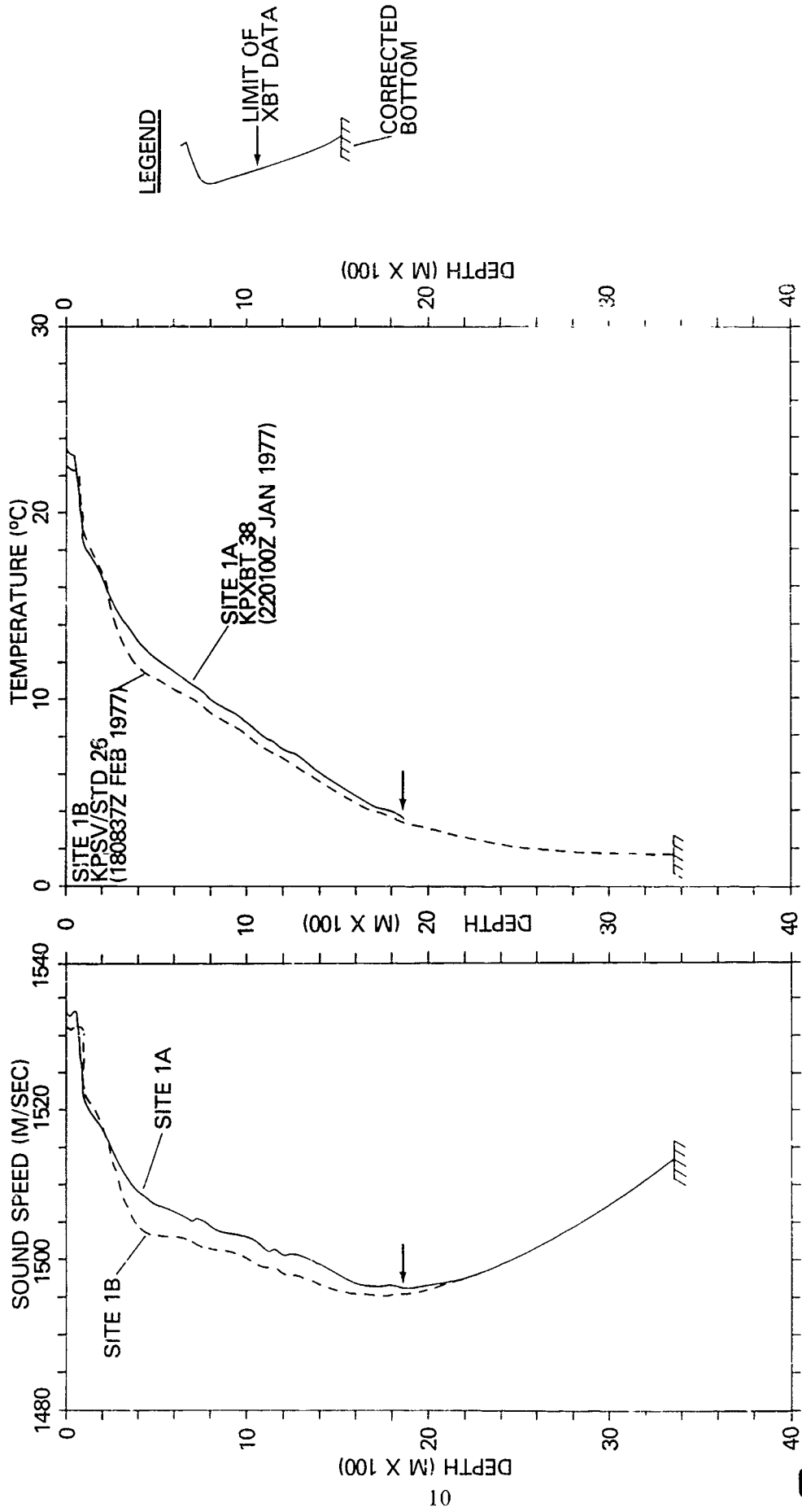


Figure 5.(U) Comparison of sound speed and temperature profiles during KJNGSPORT events S1 at site 1A and S1 at site 1B (U)

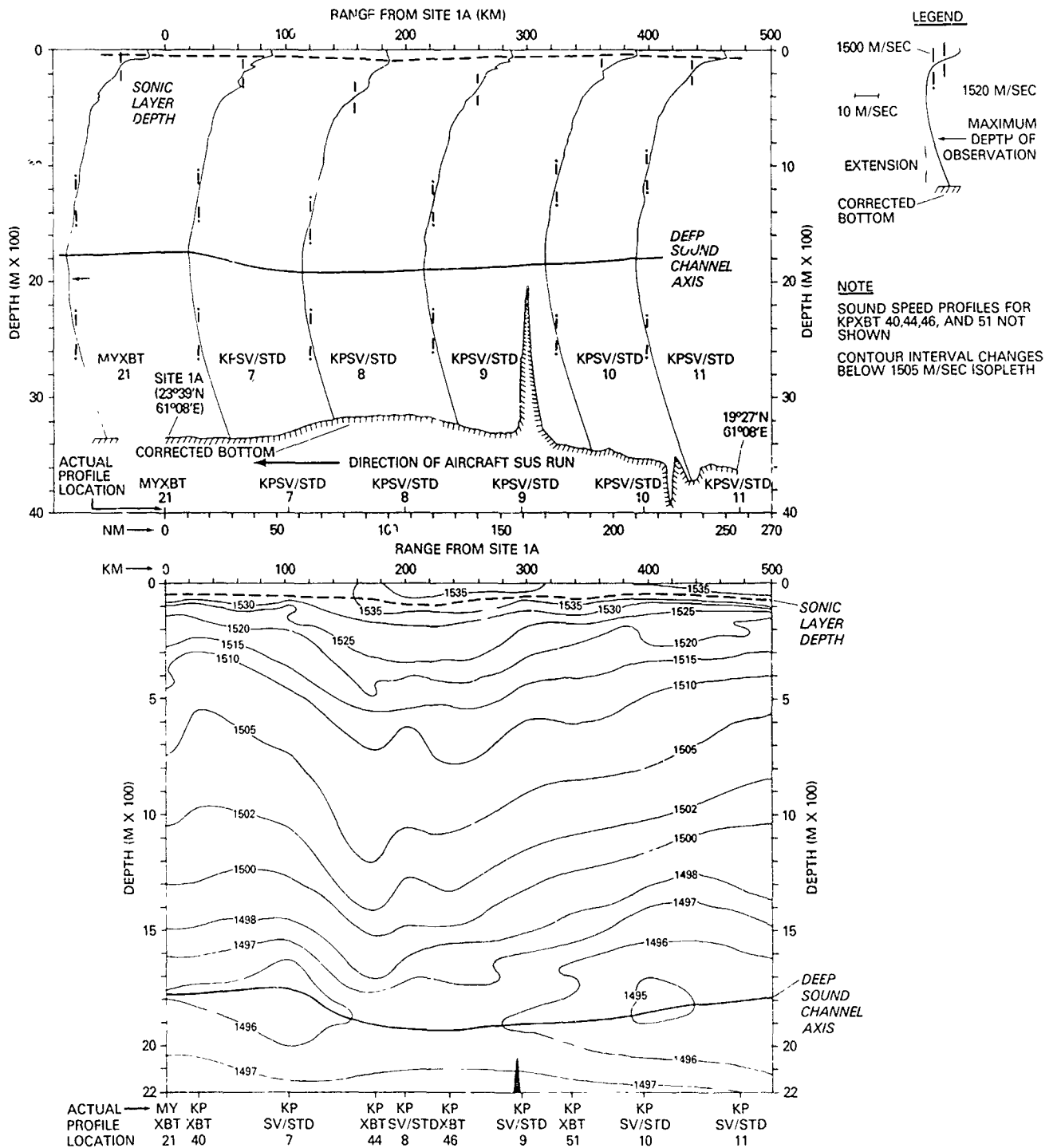


Figure 6.(C) Sound speed structure along KINGSFORT 1A1 track (site 1A) (U)

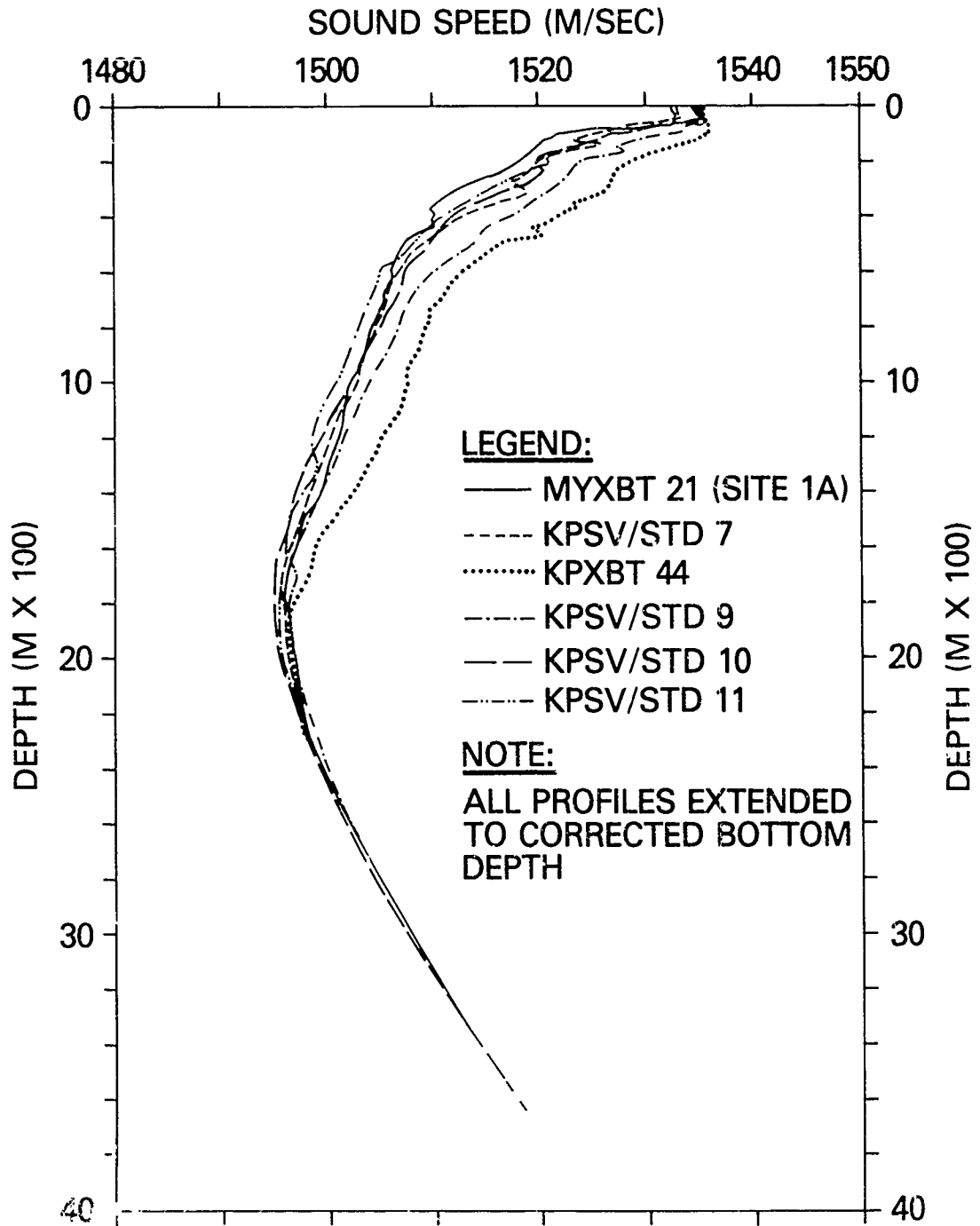


Figure 7.(U) Sound speed overplot along KINGSPORT 1A1 track (site 1A) (U)

depth were greatest at a range of 110 nm (about 200 km) from site 1A. This range apparently marks the center of an anticyclonic cell. The sound speed profile in the center of this cell (KP XBT 44 shown on Figure 7) is several meters-per-second higher than that for profiles surrounding it. The anticyclonic nature of this cell is confirmed by the sharp declination of the 1497- to 1520-m/sec isopleths at ranges greater than 50 nm (about 90 km) followed by a more gradual isopleth inclination at ranges greater than 120 nm (about 220 km). A similar anticyclonic cell is evident in the winter (December-February) surface dynamic topography of the northern Arabian Sea (Duing, 1970). The corrected bottom along the entire KINGSPORT track was shallower than either critical or 90-m conjugate depth. Maximum sound speed variability along the track (about 14 m/sec) occurred at a depth of about 100 m.

#### V. (U) ENVIRONMENTAL VARIABILITY AT SITE 3

(C) Site 3 was located in the central Arabian Sea, and as previously mentioned was not markedly influenced by intrusive water masses. Only RSIW caused significant microstructure on Site 3 sound speed profiles (at depths between about 400 and 900 m). The environmental summary for this site is presented as Figure 8. A sonic layer was present during the first five days, but later was masked by surface insolation. The depth of the DSC remained quite constant (1720-1850 m) and the axis showed a sound speed variation of less than 2 m/sec. The maximum temporal variation in the water column occurred at about 100 m, and was only about 5 m/sec. Overall, temporal sound speed variability at site 3 was less than at any other exercise site, and meteorological conditions were very nearly constant. Wind speeds averaged about 5 m/sec and were associated with sea and swell heights of less than 2 m. As was the case at sites 1A and 1B, site 3 was bottom-limited in respect to both the high frequency (18-m) and low frequency (91-m) CW sources.

(C) Figure 9 shows a contoured sound speed cross section along the KINGSPORT 3A2 track. An overplot of selected sound speed profiles along this track is given in Figure 10. The KINGSPORT 3A2 track corresponds to an aircraft SUS event flown between 080850Z and 081021Z February 1977. The XBTs and SV/STDs along the track were taken 3-5 days after the aircraft event. A sonic layer was present along most of the section at depths between 20 and 80 m. At site 3 (M7 XBT 47) surface insolation masked the layer, while at ranges between 100 and 200 nm (about 180 and 380 km) surface insolation caused the sonic layer to shoal to about 20-m depth. The depth of the DSC axis gradually inclined to the southwest from 1900 m at site 3 to 1775 m at a range of 310 nm (about 575 km), and displayed a sound speed variability of about 3 m/sec. At depths between about 400 and 900 m, RSIW caused small sound speed perturbations in the negative sound speed gradient underlying the permanent thermocline. These perturbations took the form of microstructure with vertical extents less than 100 m. The corrected bottom along the entire track was shallower than either critical or 90-m conjugate depth. The greatest spatial sound speed variability in the water column (about 5 m/sec) occurred at about 100-m depth. Two other sound speed cross sections radial to site 3 (for KINGSPORT events P2 and P4) are presented in Appendix A as Figures 24 and 25, respectively. Both sections have been discussed in the BEARING STAKE Acoustic Assessment Report (NOSC, 1978).

#### VI. (U) ENVIRONMENTAL VARIABILITY AT SITE 4

(C) Site 4 was located atop the Chain Ridge with acoustic tracks oriented north and west across the western Somali Basin. Environmental variability at site 4 was the most complex found at any exercise site due to intermixing of five intrusive water masses (PGIW, SSW, RSIW, AAIW, and BIW). Figure 11 presents a temperature, salinity, and sound speed profile plus a T-S diagram for a location about 30 nm (55 km) northwest of site 4 (see location on inset to Figure 13) that is generally representative for the site itself. BIW is not present on the Figure 11 T-S diagram, but can be found sporadically in the vicinity of site 4 at a sigma-t of about 27.40 (see Figure C-7 of Fenner and Bucca, 1972b). PGIW and AAIW also may be absent at site 4. However, during BEARING STAKE, AAIW was present at the site throughout the occupation, and PGIW was present throughout most of the occupation. In terms of sound speed structure, RSIW was the most influential water mass and was present throughout the western Somali Basin during March 1977.

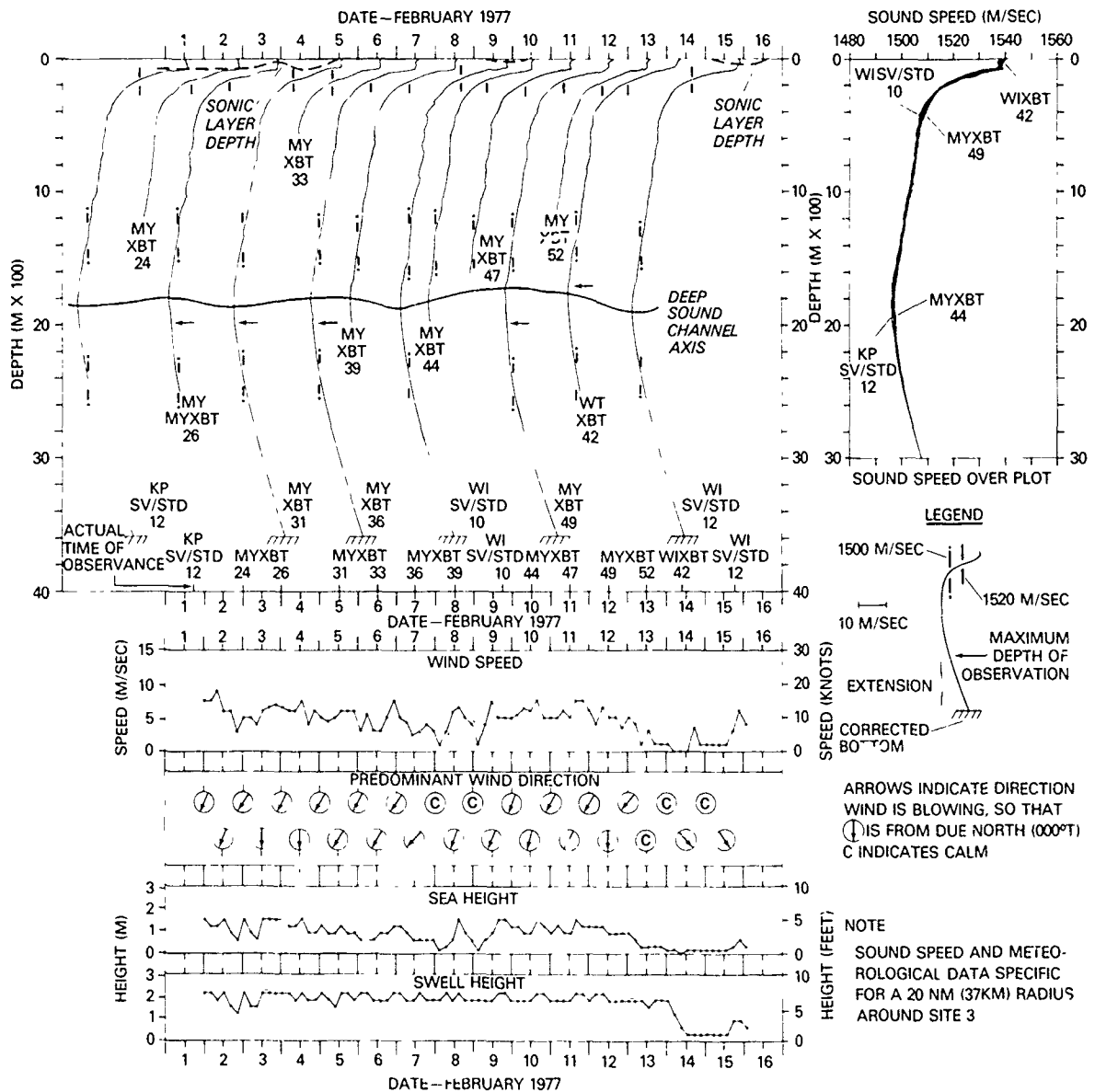


Figure 8.(U) Environmental summary at site 3 (1-16 February 1977) (U)

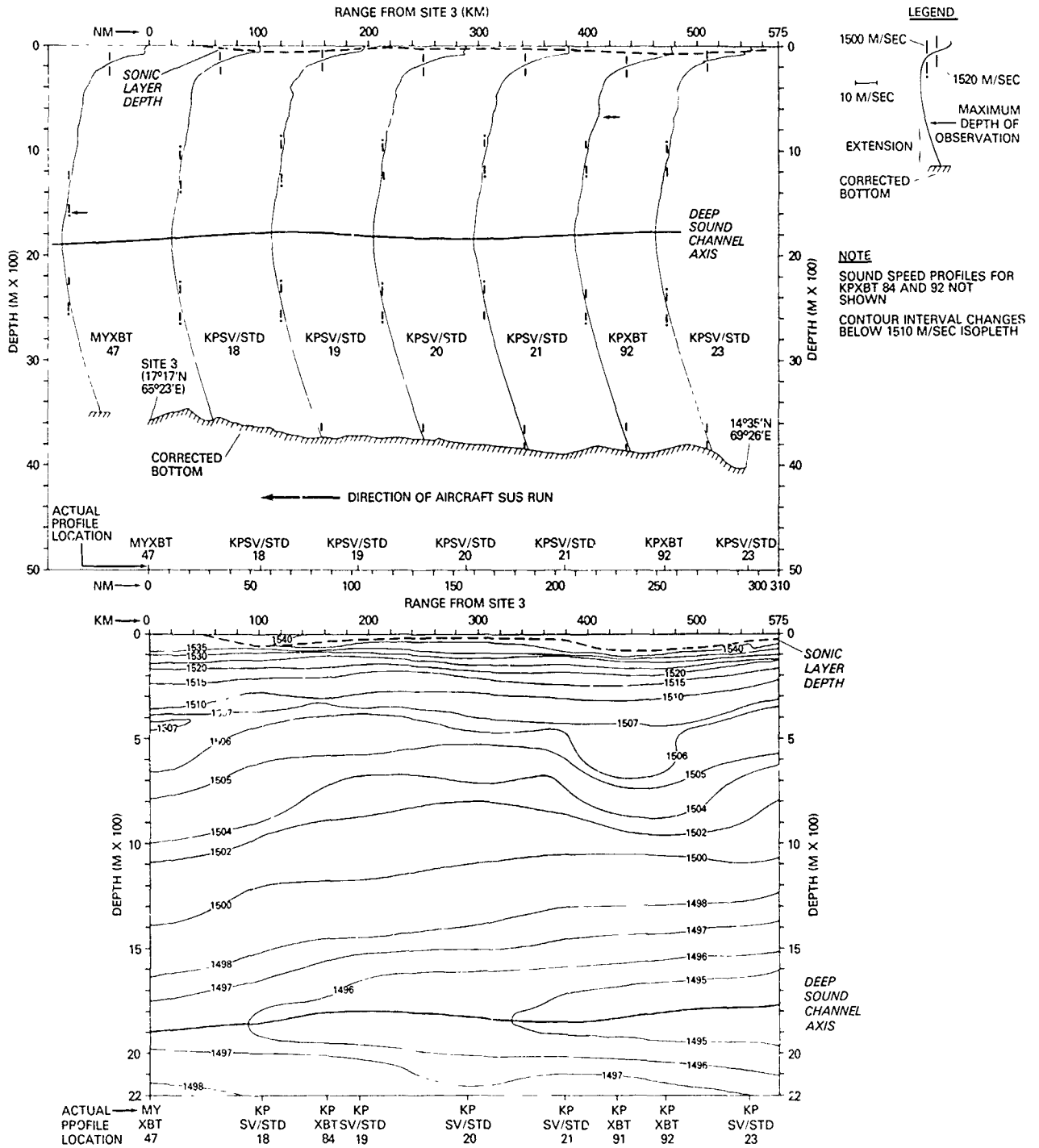


Figure 9.(C) Sound speed structure along KINGSPORT 3A2 track (site 3) (U)



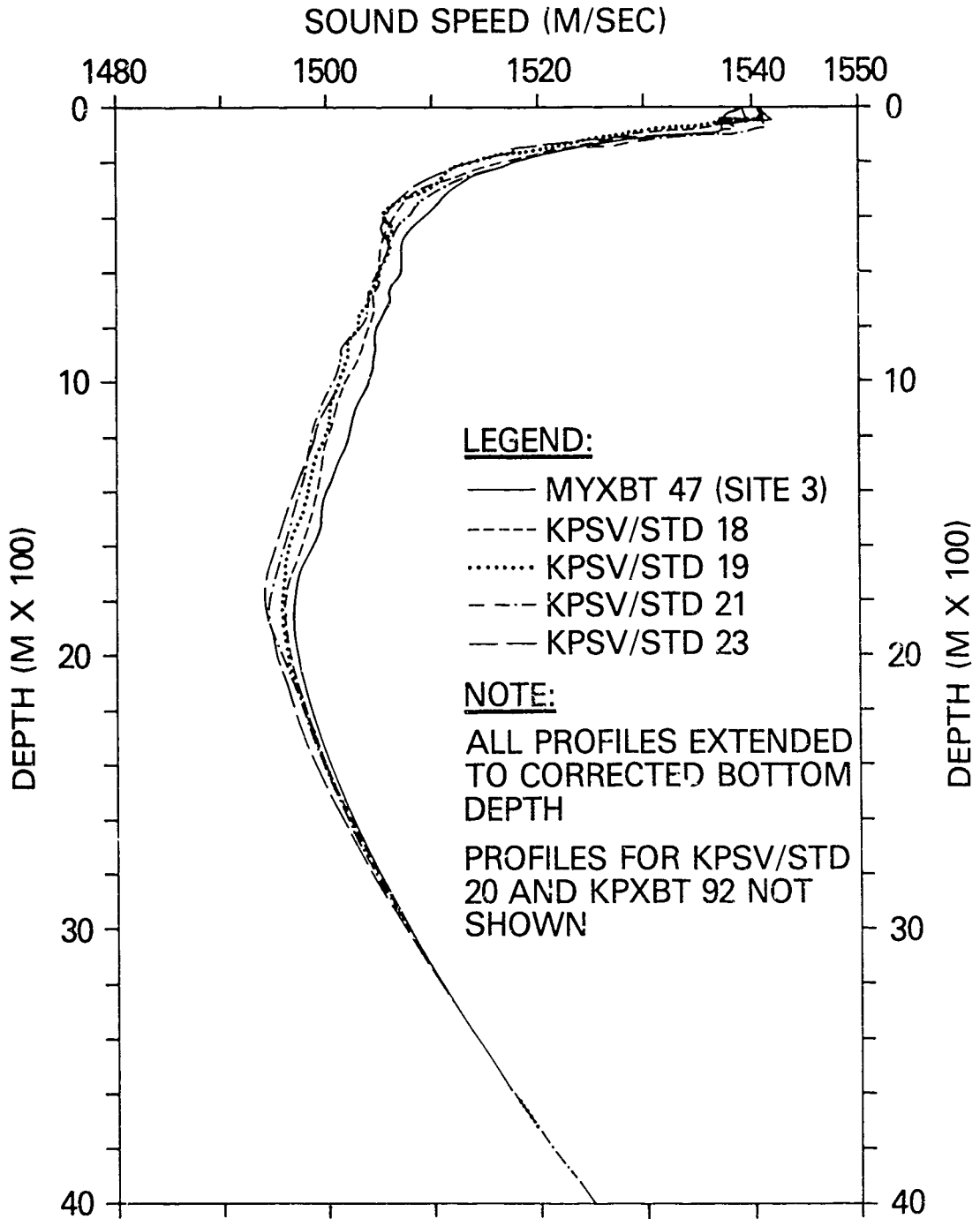


Figure 10.(U) Sound speed overplot along KINGSPORT 3A2 track (site 3) (U)

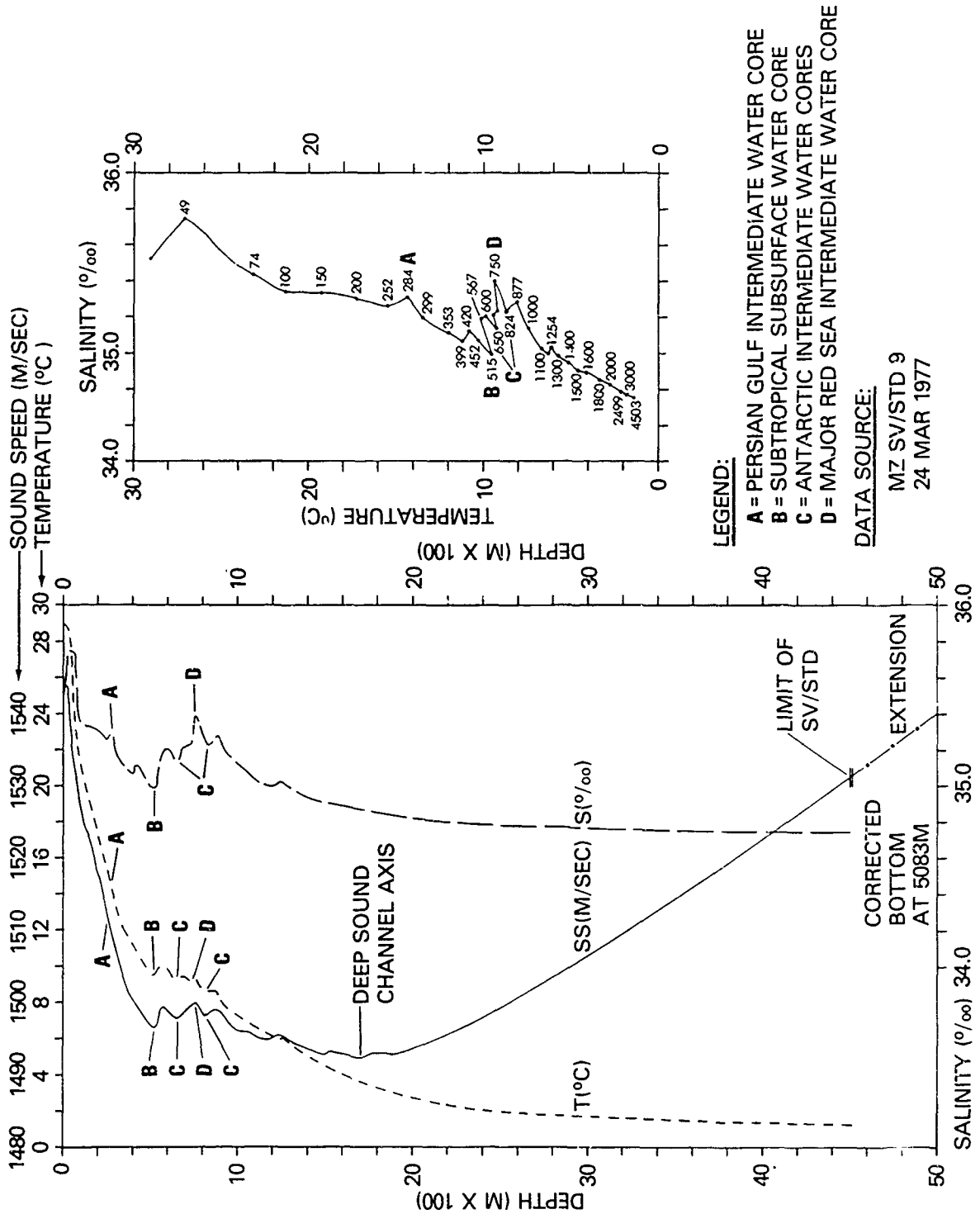


Figure 11.(U) Temperature-salinity-sound speed profiles near site 4 during short-period time-series (U)

## A. (U) Temporal Variability

(C) The environmental summary for site 4 (including an 18-day time-series plot of sound speed) is given in Figure 12. Throughout the occupation, sound speed profiles displayed extremely variable microstructure between about 300 and 1800 m. As previously mentioned, this microstructure was caused by mixing of PGIW, SSW, RSIW, and AAIW and by sinking of RSIW as a result of this intermixing. A sporadic sonic layer frequently was present, but was not a permanent feature at site 4. Over 18 days, the depth of the DSC lay between 1600 and 1850 m, with a sound speed variability of 3-4 m/sec. At 100 m, just below the depth of the low frequency CW source (91 m), sound speed varied by more than 17 m/sec, the greatest temporal variability encountered at any exercise site. Although the corrected bottom depth at site 4 was 5109 m (deepest of any exercise site), site 4 was effectively bottom-limited throughout the occupation. Before 17 March, 90-m conjugate depth was about 200 m shallower than the bottom. However, between 17 and 21 March, 90-m conjugate depth shoaled to a level about 700 m above the bottom. The rapid decrease in 90-m conjugate depth was caused by a cooling of the main thermocline that also resulted in a change of shape of the sound speed profile above a depth of about 200 m. Wind speeds at site 4 averaged 5 m/sec, accompanied by approximately 1-m seas and 2-m swells.

(C) Figure 13 shows a 78-hour time-series plot of sound speed and temperature profiles at a location 20 nm (37 km) northwest of the nominal site 4 position (Fig. 1). The locations of the XBTs and two MIZAR SV/STDs used in this time-series are shown on an insert to Figure 13. A T-S analysis for one of the two SV/STDs (MZ SV/STD 9) is presented on Figure 11, and indicates that PGIW, SSW, RSIW, and AAIW were present and actively interleaving during the 78-hour time-series. All XBTs used in the time-series were taken by WILKES, alleviating relative XBT recorder inaccuracies.

(U) The intense sound speed microstructure shown in Figure 13 is continuous throughout most of the 78-hour sample period. The predominant upper sound speed minimum (i.e., the minimum with the lowest sound speed in the upper water column) generally occurred at about 500 m, and generally corresponded to the depth of the low salinity SSW core. The predominant intermediate sound speed maximum (i.e., the maximum above the DSC axis with the highest sound speed) generally occurred between 600 and 800 m, and corresponded to one of the several high salinity RSIW cores. However, on 23 March (WI XBTs 153 and 161), the predominant upper sound speed maximum actually lay above the depth of the upper minimum, but still corresponded to an RSIW salinity maximum. At the site of the 78-hour time-series, and at site 4 itself, AAIW was actively mixing out the high salinity RSIW core. Such intermixing was responsible for much of the complex sound speed microstructure shown on Figures 12 and 13. PGIW did not cause sound speed perturbations during the short-period time-series, but did cause gradient changes above a depth of about 300 m when present. BIW apparently was not present northwest of site 4 but may have been sporadically present at site 4 itself.

(U) Over the 78-hour time-series (Fig. 13), a sonic layer generally was not present due to surface insolation. A similar situation was found at site 4 during the 18-day time-series (Fig. 12). The depth of the DSC axis varied between 1580 and 1790 m over 78 hours (total variation of 210 m). This variation is of the same magnitude as the 250-m variation in axial depth found at site 4 over a period of 18 days. Variations in axial sound speed (3-4 m/sec) also were comparable for the 18-day and 78-hour time-series. The fact that the fluctuations in axial depth and sound speed were approximately the same over 78-hour and 18-day samples implies that the fluctuations were random.

## B. (U) Spatial Variability

(C) Figure 14 shows a contoured sound speed cross section along the KINGSPORT 4A1 track corresponding to an aircraft SUS flight made between 200611Z and 200756Z March 1977. The track was occupied by KINGSPORT 1-4 days after the aircraft event. Figure 15 shows an overplot of selected sound speed profiles, and Figure 16 presents T-S diagrams for each of the KINGSPORT SV/STDs along the track. A sonic layer occurred along most of the section, but was shallow (20-30 m) and relatively ill defined. The greatest spatial sound speed variability (about 18 m/sec) occurred at 150-m depth within the permanent thermocline. Despite the greater than 5000-m depths of the Somali Basin, the track was basically bottom-limited. Along the first 250 nm (about 460 km) of track, the corrected bottom was

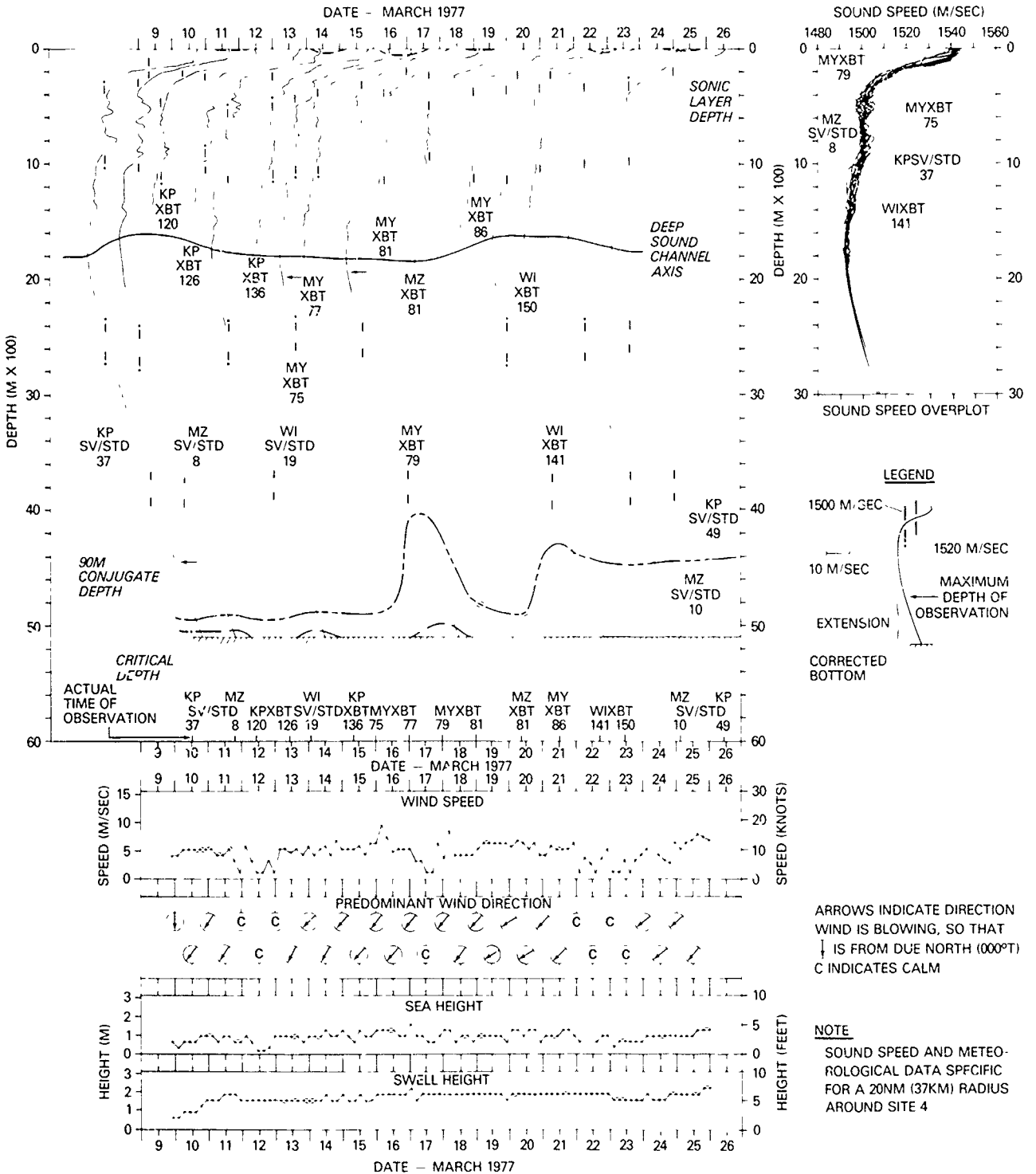


Figure 12.(U) Environmental summary at site 4 (9-26 March 1977) (U)

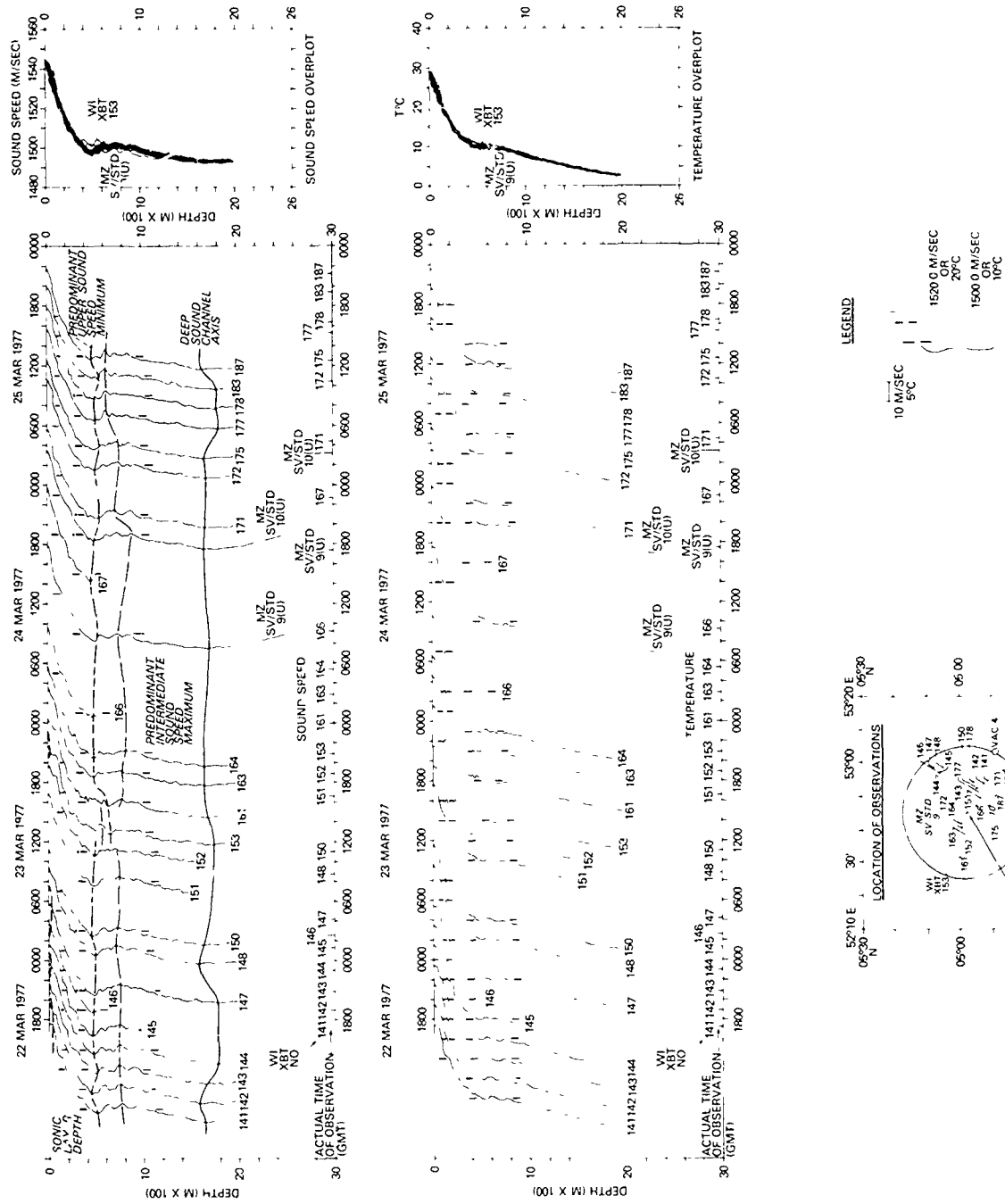


Figure 13.(C) Short-period variability in sound speed and temperature near site 4

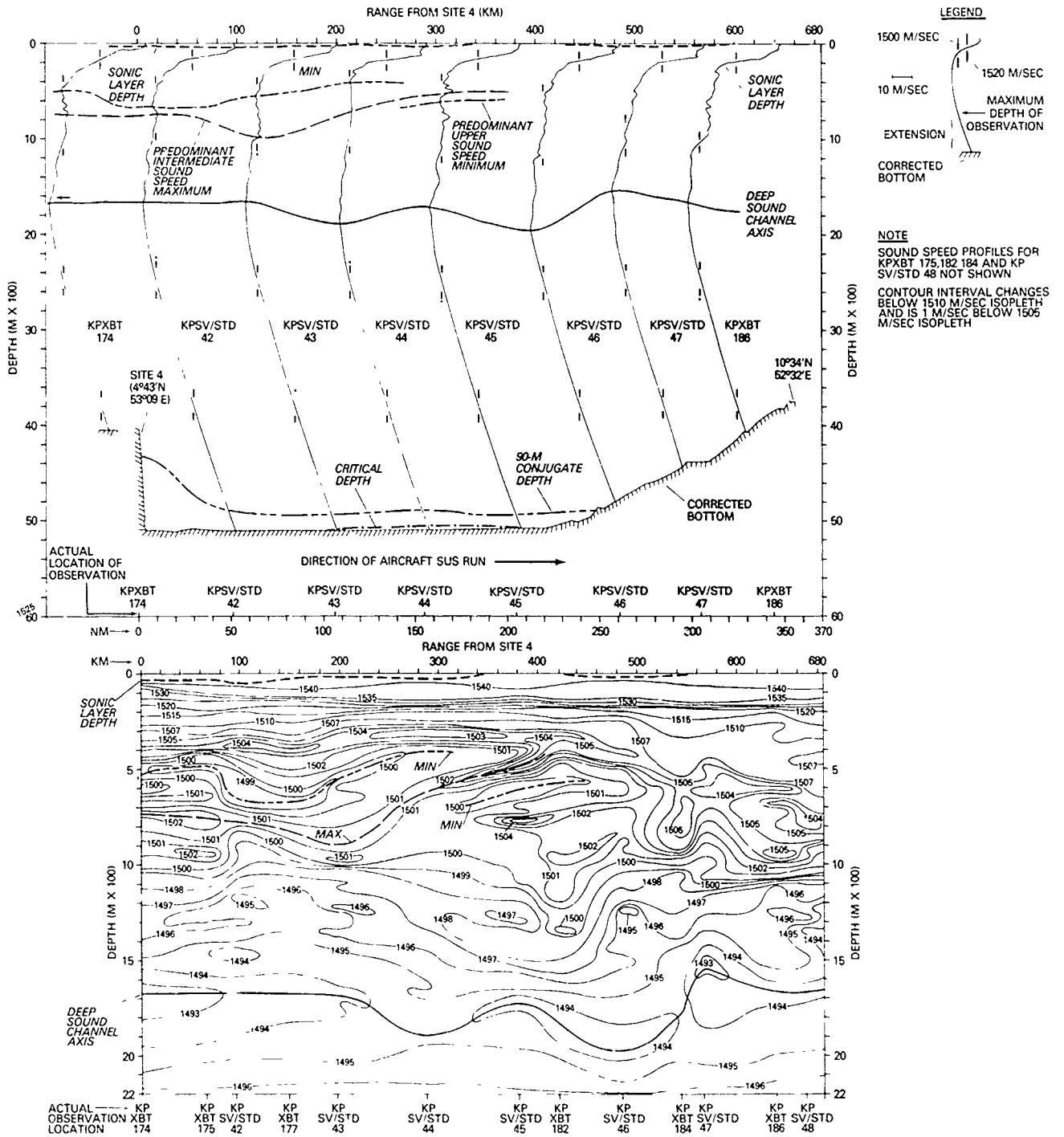


Figure 14.(C) Sound speed structure along KINGSFORT 4A1 track (site 4) (U)

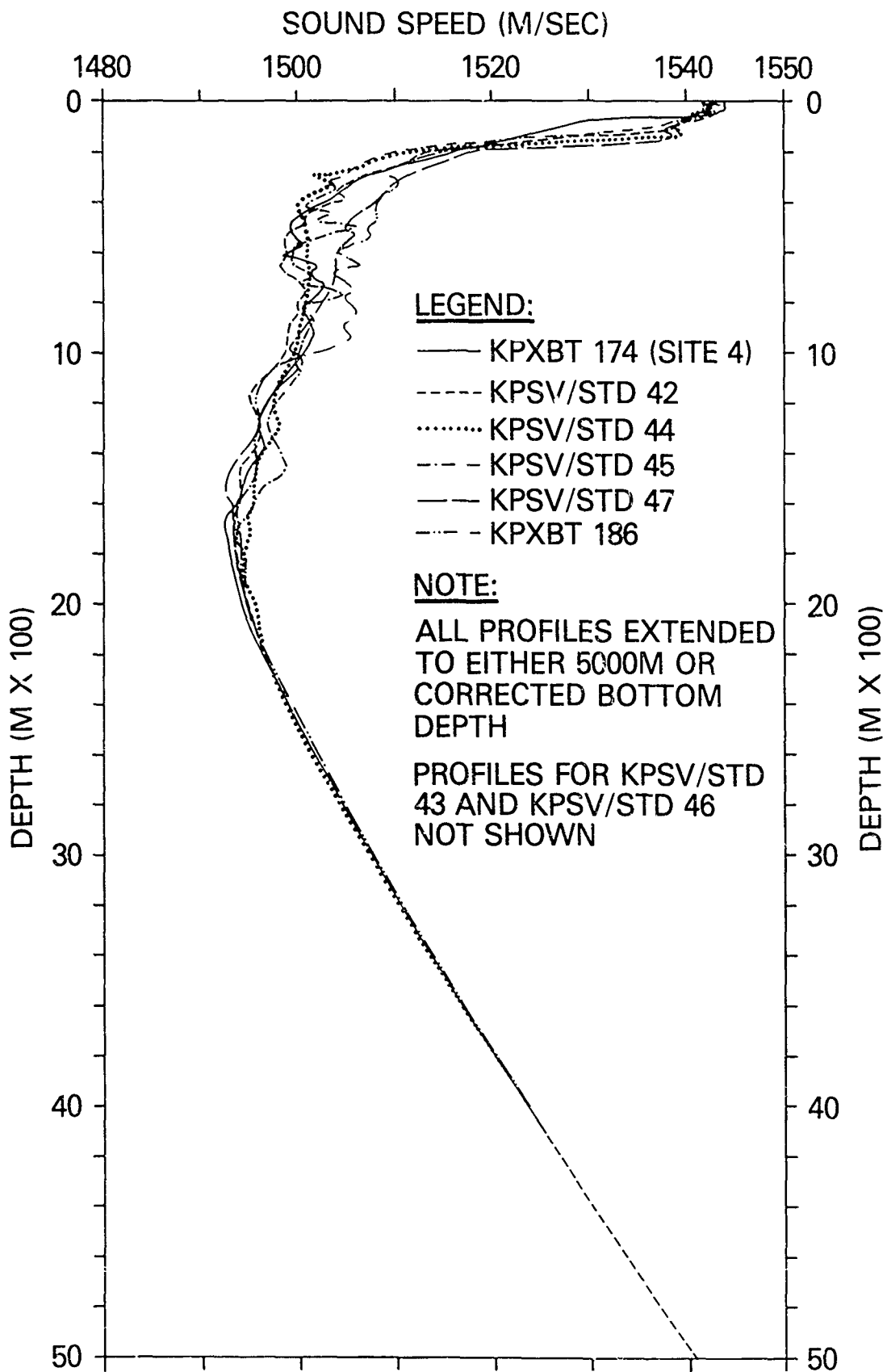


Figure 15.(U) Sound speed overplot along KINGSPO RT 4A1 track (site 4) (U)

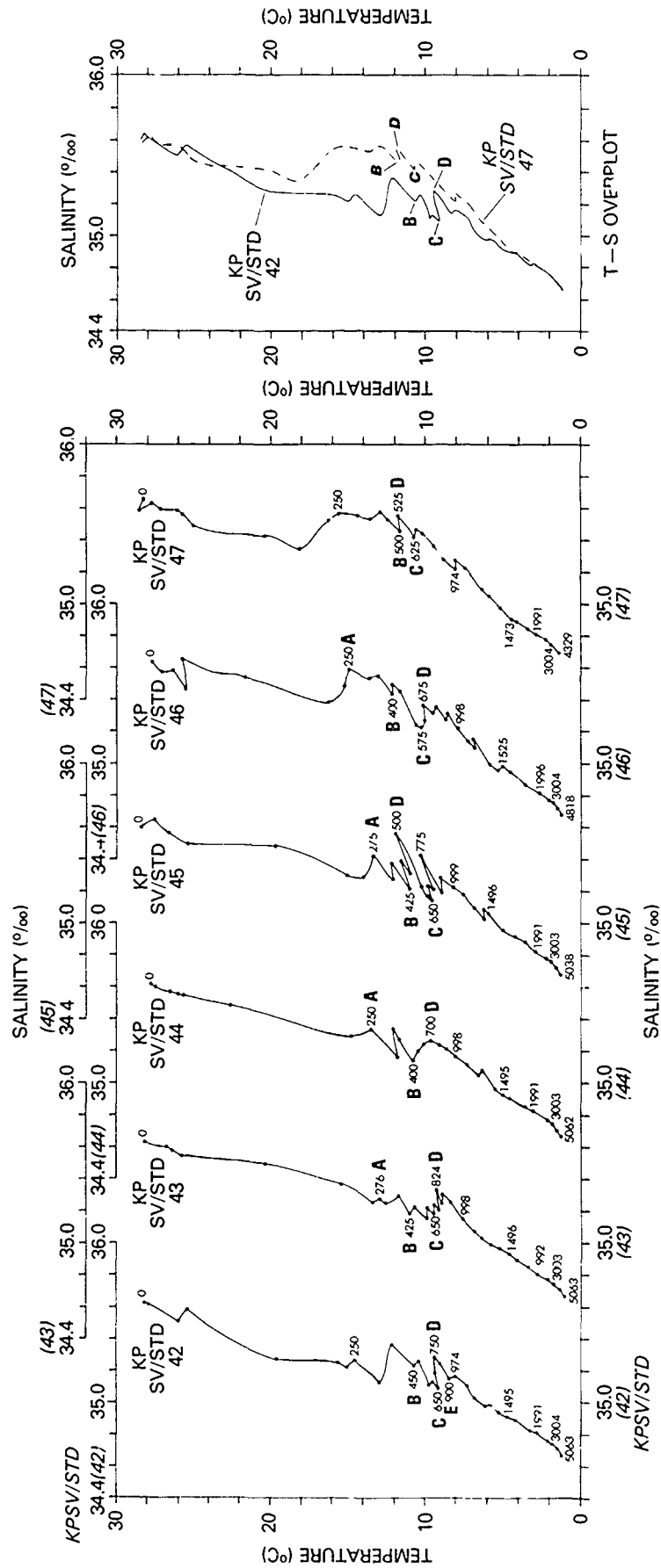


Figure 16.(U) Temperature-salinity diagrams along KINGSPORT 4A1 track (site 4) (U)



at least 200 m deeper than 90-m conjugate depth. Near site 4, however, the corrected bottom was up to 800 m deeper than 90-m conjugate depth due to a cooling of the main thermocline. A similar cooling was found in the 18-day sound speed time-series (Fig. 12) after 17 March.

(U) DSC structure along the KINGSPORT 4A1 track varied more than that along any other exercise acoustic track. Axial sound speed varied by about 3 m/sec, while axial depth varied between 1550 and 1920 m. All of the variation in axial depth occurred between ranges of 261 and 305 nm (484 and 567 km). Here, the depth of the DSC had a gradient of 8.4 m/nm (4.5 m/km). Although this gradient is only one-fifth that found across Gulf Stream fronts in the North Atlantic Ocean (Fenner, 1978), it is the largest such gradient found along exercise acoustic tracks and demarks the location of an oceanic frontal zone at 9°-10°N. This front caused a discontinuity in the sonic layer and marked the northern boundary of double minimum sound speed profiles. Within the frontal zone, RSIW was intensively mixed with PGIW, SSW, and AAIW, causing the rapid declination of the 1502- through 1507-m/sec sound speed isopleths. At the approximate location of this frontal zone, the major flow of RSIW east of Socotra (Fig. 1) breaks into several preferential flows (see Figure C-5 of Fenner and Bucca, 1972b). In this same general region surface dynamic topography charts for March-April (Duing, 1970) show the juxtaposition of a cyclonic and anticyclonic cell resulting in a surficial front. The frontal zone at the northern end of the KINGSPORT 4A1 track also corresponds with the beginning of the continental rise south of Socotra.

(U) The contoured presentation on Figure 14 shows a bewildering variety of interleaving sound speed minima and maxima. South of the frontal zone at 9°-10°N, the predominant maxima were associated with the most saline RSIW core, and most of the predominant minima were associated with the SSW low salinity core. An exception is KP SV/STD 42, where the predominant minimum corresponded to the low salinity AAIW core (compare sound speed profile on Figure 14 with T-S diagram on Figure 16). A similar situation occurred at the southern end of the frontal zone (KP SV/STD 45). Here, however, the predominant minimum became discontinuous. Intermixing of AAIW and RSIW clearly was responsible for much of the complex sound speed microstructure found at site 4 and throughout the western Somali Basin during March 1977. A similar interleaving of water masses was observed throughout the region by Warren, et al. (1966) during the southwest monsoon based on Nansen cast data.

(C) The extensive mixing portrayed in Figure 14 also may be seen on two other sound speed cross sections given in Appendix A: Figure 26 (KINGSPORT event P1) and Figure 27 (KINGSPORT event P5). Both tracks were bottom-limited. However, the corrected bottom along each track was approximately 200 m deeper than 90-m conjugate depth. The greatest sound speed variability along both tracks occurred at about 150 m, below the nominal tow depth of the low frequency source. A sonic layer was absent along both tracks, probably due to surface insolation. Generally, sound speed structure along both tracks was less complicated than that along the KINGSPORT 4A1 track (Fig. 14). However, individual sound speed profiles were quite irregular and clearly showed the effects of intermixing of SSW, RSIW, and AAIW.

## VII. (U) ENVIRONMENTAL VARIABILITY AT SITE 5

(C) Site 5 lay at the southern edge of the Arabian Basin on the flanks of the Carlsberg Ridge, and, as previously mentioned, was under the influence of a strong, preferential flow of RSIW. The environmental summary for site 5 is presented as Figure 17. Unfortunately, only one good SV/STD was available at site 5, and the majority of XBTs dropped within 20 nm (37 km) of the site failed at depths shallower than the DSC. All sound speed profiles shown on Figure 17 displayed a sound speed minimum at about 400 m depth associated with SSW. Two of the profiles (KP SV/STD 50 and MY XBT 100) showed a significant sound speed perturbation at the top of the permanent thermocline (30-100 m). Similar structures are encountered in much of the March-April historical data collected near site 5 by the International Indian Ocean Expedition and also were found sporadically along most site 5 acoustic tracks. A sonic layer was not persistent at site 5. The greatest temporal sound speed variability in the water column (about 15 m/sec) occurred at about 150 m, below the depth of the low frequency (91-m) source. Acoustic propagation at site 5 was bottom-limited for both the low and high frequency sources. The DSC structure shown on Figure 17 is speculative, since most of the XBTs failed at depths less than 1500 m. Meteorological conditions were moderate throughout the 12-day occupation of site 5, with wind speeds less than 6 m/sec, sea heights generally less than 1 m, and swell heights averaging less than 2 m. Two sound speed cross

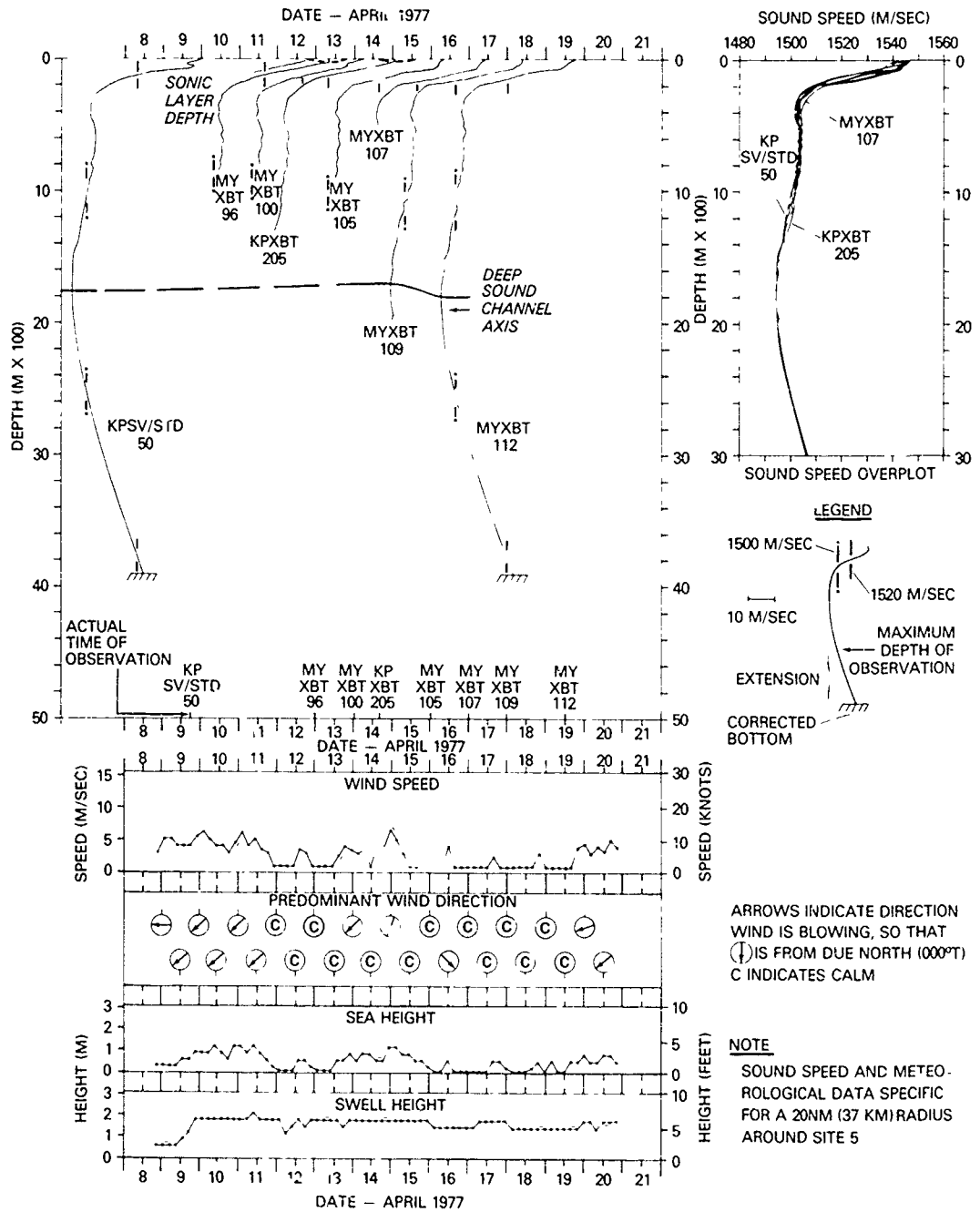


Figure 17.(U) Environmental summary at site 5 (8-21 April 1977) (U)

sections along tracks radial to site 5 are presented in Appendix A: Figure 28 (KINGSPORT P1 track) and Figure 29 (KINGSPORT P5 track). Both sections have been discussed in the BEARING STAKE Acoustic Assessment Report (NOSC, 1978).

#### VIII. (U) ENVIRONMENTAL VARIABILITY AT SITE 2

(C) Site 2 lay on the Owen Ridge north-northwest of the mouth of the Gulf of Aden. Sound speed structure at this site was strongly influenced by both PGIW and RSIW. However, neither water mass caused distinct sound channels at site 2, only microstructure. The environmental summary for this site is presented as Figure 18. Unfortunately, no reliable SV/STD data were collected during the site 2 occupation. Based on MYER XBT data, temporal sound speed variability at site 2 was less than that at other exercise sites except site 3. A maximum variation of about 5 m/sec occurred between 100 and 150 m, below the depth of the low frequency (91-m) source. A sonic layer was absent at site 2 throughout the 9-day occupation, and acoustic propagation was bottom-limited for both the high frequency (18-m) and low frequency sources. The DSC lay between about 1720 and 1900 m and displayed a variability of less than 2 m/sec. Wind speeds were generally calm at site 2, as would be expected for the end of the intermonsoonal period. The southwest monsoon had not started during the site 2 occupation. Wave heights were generally less than 1 m superimposed on about 2-m swells. Two sound speed cross sections radial to site 2 are presented in Appendix A: Figure 30 (KINGSPORT P1 track) and Figure 31 (KINGSPORT P3 track). Both sections are discussed in the BEARING STAKE Acoustic Assessment Report (NOSC, 1978).

#### IX. (U) REPRESENTATIVE SOUND SPEED AND TEMPERATURE-SALINITY PROFILES

(U) Composites of representative BEARING STAKE sound speed profiles and their associated T-S diagrams are illustrated in Figure 19. The representative profiles were derived from the time-series plots of sound speed for each site, and generally are a near-modal profile. For all sites except site 2, the representative exercise sound speed profiles are based upon SV/STD data so as not to incorporate XBT inaccuracies. Near-surface temperatures and sound speeds at sites 1A/1B were somewhat lower than those at other exercise sites due to the effects of northeast monsoon upwelling in the northern Arabian Sea. As previously mentioned, sound speed profiles at sites 1A and 1B varied markedly at about 400-m depth, probably attributable to northeast monsoon upwelling. Representative T-S diagrams for these two sites clearly show that temperature at 400 m was more than 1°C warmer at site 1A than at site 1B, while salinity at 400 m was about 0.2‰ higher at site 1A. At depths above 1200 m, the representative sound speed profile at site 2 was several meters-per-second higher than that for other exercise sites, caused by high salinity PGIW and RSIW in a relatively unmixed form. The microstructure shown on the site 2 representative profile was caused by intermixing and sinking of these two water masses. In contrast, the representative profile for site 3 was smooth and regular and showed minimal water mass effects.

(U) At site 4, the extremely complex and irregular sound speed and T-S profiles reflect intermixing of PGIW, SSW, RSIW, and AAIW. Between depths of about 400 and 2500 m, the representative sound speed profile at site 4 was the lowest encountered at any exercise site, due mainly to the southern location of the site and to the effects of relatively cool, low salinity SSW and AAIW. Although site 5 was influenced by both SSW and RSIW, the oceanography there was nowhere near as complex as at site 4. Due to its location just north of the Carlsberg Ridge, the representative sound speed profile at site 5 closely resembled that for site 3 below 700 m. However, above 700 m, the profile at site 5 exhibited a bichannel structure similar to that for site 4. Sound speed profiles in the vicinity of site 5 frequently displayed perturbations at depths above 100 m that were caused by a near-surface, low salinity layer overlying warmer, more saline waters from the northern Arabian Sea.

(U) Figure 20 compares representative exercise sound speed profiles at each site with representative profiles from the southwest monsoon (June-September). All profiles presented in Figure 20 are listed in Appendix B (Tables 3, 4, and 5). The representative southwest monsoon profiles were chosen from historical data positioned as close to each site as possible and therefore are not specific to any oceanic province. At sites 1A/1B, the representative southwest monsoon profile was nearly 10 m/sec higher at the surface than that found during the exercise due to the effects of summer warming. At site 3, summer

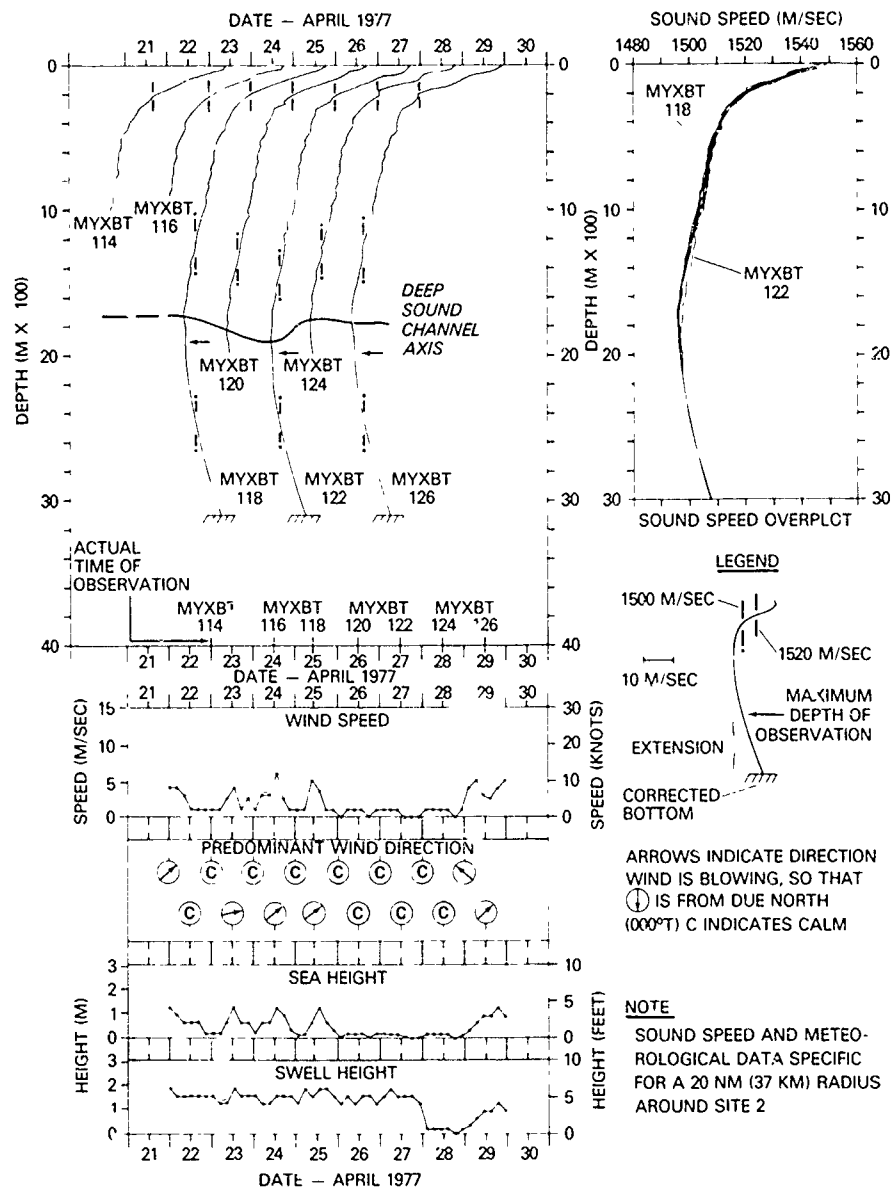


Figure 18.(U) Environmental summary at site 2 (21-30 April 1977) (U)

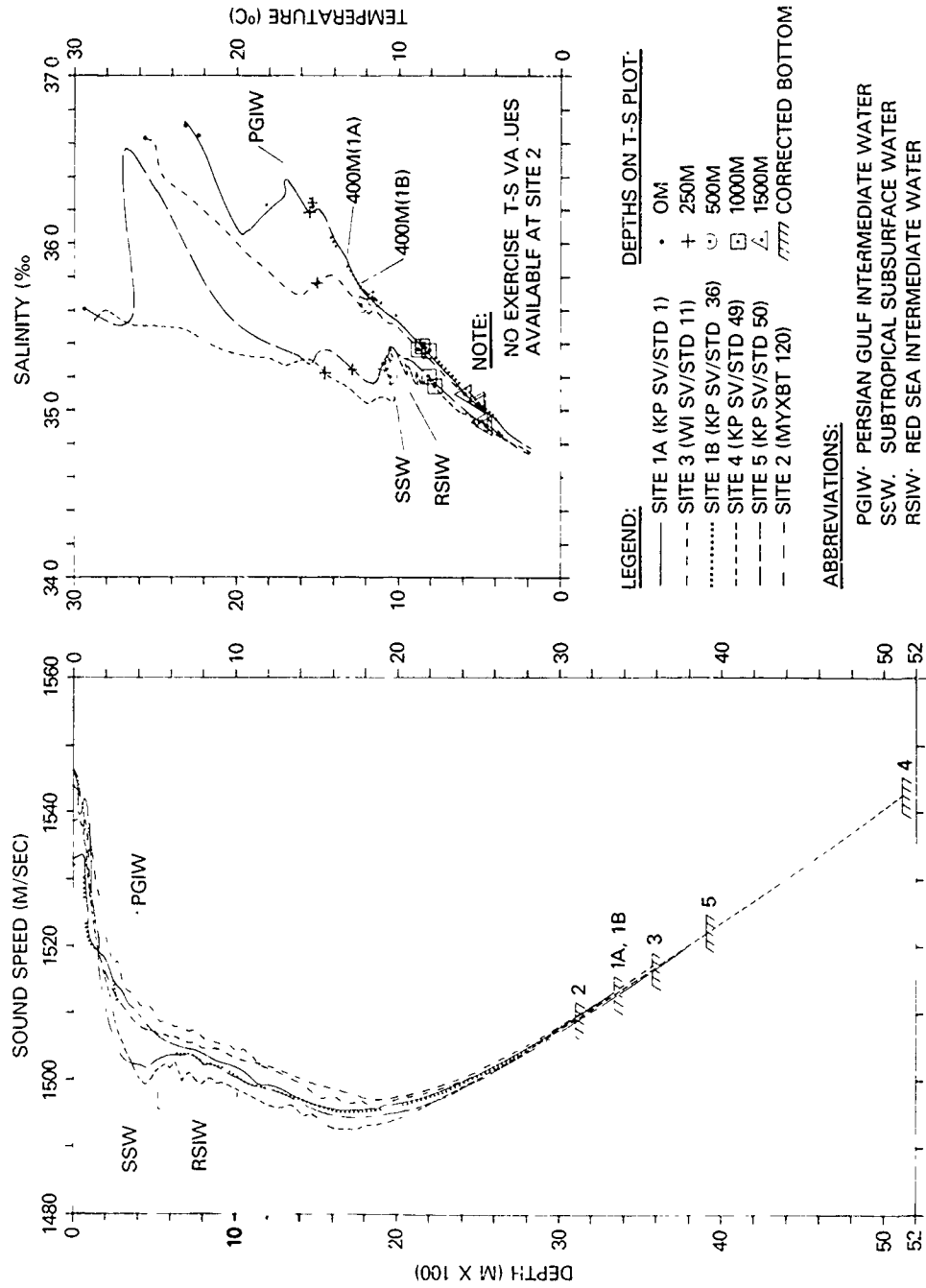


Figure 19.(U) Representative sound speed and temperature-salinity profiles at each site (U)

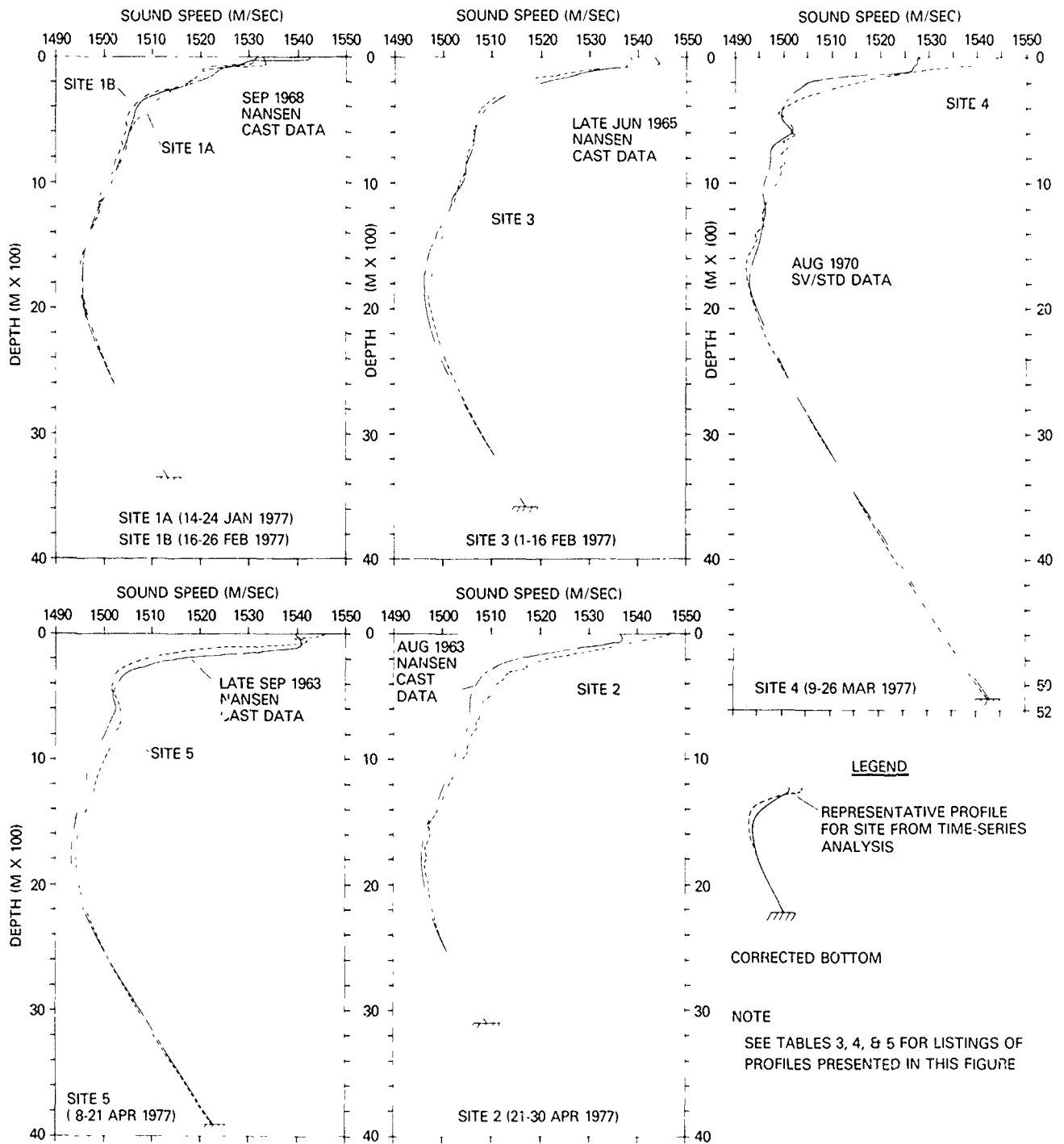


Figure 20.(C) Comparison of representative exercise and southwest monsoon sound speed profiles at each site (U)

warming caused an approximately 5-m/sec increase in surface sound speed during the southwest monsoon. At site 4, the southwest monsoon profile was 17 m/sec lower at the surface than the exercise profile, apparently due to summer upwelling off the Somali coast. This upwelling caused lower southwest monsoon sound speeds to a depth of at least 400 m. At site 5, the southwest monsoon profile was about 15 m/sec higher than the exercise profile above 400-m depth, due to both near-surface warming and the effects of reversing monsoon circulation. In addition, the upper sound speed minimum was far better developed during the exercise, probably due to the presence of more RSIW. At site 2, southwest monsoon upwelling off the Muscat and Oman coasts caused lower sound speeds to depths of at least 500 m. Below 400-500 m, representative sound speed profiles at all sites were quite similar to those for the exercise except in regions where upwelling is expected during summer, in keeping with the findings of Fenner and Bucca (1972b). In any case, the southwest monsoon profiles shown in Figure 20 are adequately representative for acoustic modeling during the southwest monsoon.

## X. (U) ACOUSTIC IMPLICATIONS

(C) Except for site 4, acoustic propagation at the major BEARING STAKE sites was bottom-limited for both the high frequency (generally 18-m) and low frequency (generally 91-m) CW sources. Therefore, details of acoustic propagation are governed more by details of bottom interaction than by sound speed variability, unless this variability occurred at or above the depth of the source. The depth of maximum temporal and spatial sound speed variability lay between 100 and 150 m at all sites and therefore was below the nominal tow depth of either the high or low frequency sources, except at site 1B. Here, the nominal tow depth of the low frequency source was 102 m, and sound speed variability should affect transmission of acoustic signals to a greater degree than at other acoustic sites. At site 1A/1B, upwelling caused a 4- to 5-m/sec change in sound speeds between the two occupations. This change would complicate comparison of propagation losses for KINGSPORT events S1 at the two sites, but should not cause markedly different propagation. At sites 2 and 3, environmental variability apparently was insufficient to markedly affect propagation. At site 5, sporadic sound speed perturbations above a depth of about 100 m could have significant effects on propagation, particularly for the low frequency source (nominal tow depth of 91 m).

(C) At site 4 and along site 4 acoustic tracks, the corrected bottom frequently exceeded 5000 m. Nevertheless, propagation was basically bottom-limited for the high frequency (18-m) source since critical depth lay barely above the corrected bottom, so that an acoustic wave propagating over the spherical earth would actually penetrate the bottom. Some refraction of downward rays would be expected from the low frequency (91-m) source throughout the Somali Basin since 90-m conjugate depth frequently lay at least 200 m above the corrected bottom. The intense sound speed variability and microstructure encountered at site 4 and along acoustic tracks radial to this site may have caused some anomalies in acoustic propagation patterns, even for bottom-limited situations. These anomalies should be most obvious for the low frequency (91-m) source in situations where the corrected bottom was deeper than 90-m conjugate depth.

(U) Ambient noise for frequencies above that where shipping dominates (approximately 200 Hz) is governed by local wind speed (Wenz, 1962). Generally, winds were calm or of low speed throughout BEARING STAKE, up to a maximum of 10.5 knots at site 1A. Thus, ambient noise levels should be low at the higher frequencies. In the event that infrasonic noise (less than 20 Hz) is explicitly due to sea and swell conditions, levels also would be low, since maximum sea and swell heights were less than 1.5 and 2.7 m, respectively, over the course of the exercise.

## XI. (U) SUMMARY

(C) The BEARING STAKE exercise was conducted at five major acoustic sites in the northwest Indian Ocean during January through April 1977. All sites were occupied during either the northeast monsoon or the transitional period between the northeast and southwest monsoons. A total of 620 XBTs, 80 SV/STDs, and more than 3200 meteorological observations (wind speed/direction and sea/swell height)

were taken throughout the exercise area to define environmental effects on acoustic propagation. In addition, bathymetric profiles were collected along all major acoustic tracks.

(U) All XBT traces were machine digitized and converted to sound speed using the equation of Wilson (1960) and a salinity field derived mainly from exercise SV/STD data. Generally, sound speeds calculated from XBT temperatures were up to 1.0 m/sec higher than those measured directly and up to 0.5 m/sec higher than those calculated from SV/STD data. Much of this error is attributable to XBT probe and recorder inaccuracies compounded by inaccuracies in Wilson's equation. Despite these inaccuracies, the total exercise sound speed data base (XBTs plus SV/STDs) is adequate for propagation loss calculations since measured and calculated sound speed gradients were nearly identical throughout the upper 2000-2500 m of the water column. Below about 3000-m depth, measured sound speeds were used exclusively in all analyses.

(C) Site 1 was located in the eastern part of the Gulf of Oman and was occupied twice, hence sites 1A and 1B. The two sites were located 5 nm (9 km) apart, and both were under the influence of high salinity PGIW that emanates into the Gulf of Oman through the Straits of Hormuz. This water mass caused sound speed perturbations above 600-m depth at site 1A (14-24 January), but only caused sound speed gradient changes at site 1B (16-26 February). Acoustic propagation at sites 1A and 1B and along acoustic tracks radial to them was bottom-limited in respect to both the high frequency (18- or 24-m) and low frequency (91- or 102-m) sources. Maximum temporal and spatial sound speed variability occurred at 100 m, the approximate tow depth of the low frequency source during site 1B acoustic events. Sound speed profiles at site 1B were up to 5 m/sec lower than those at site 1A one month earlier, apparently as a result of increased northeast monsoon upwelling after the site 1A occupation. An anticyclonic cell was found about 110 nm (200 km) south of site 1A that caused a downward bowing of sound speed isopleths in the upper 1700 m of the water column.

(C) Site 3 was located in the central Arabian Sea and was occupied during 1-16 February. This site was not strongly influenced by intrusive water masses, although high salinity RSIW did cause sound speed microstructure between about 400 and 900 m. Acoustic propagation at site 3 and along tracks radial to it was bottom-limited for both the high frequency (18-m) and low frequency (91-m) sources. Maximum temporal and spatial sound speed variability at the site (about 5 m/sec) occurred at 100 m, just below the nominal depth of the low frequency source. Overall, sound speed variability at site 3 and along acoustic tracks radial to it was less than at any other exercise site.

(C) Site 4 was located atop the Cham Ridge with acoustic tracks oriented across the western Somali Basin. The site was occupied from 9 to 26 March at the beginning of the intermonsoonal transition. In contrast to site 3, environmental variability at site 4 was the most complex found at any exercise site due to intermixing of several intrusive water masses. The site was located astride a primary flow of RSIW that extends south along the east African coast at depths of 600-900 m and also was strongly influenced by low salinity SSW and AAIW that flow north at depths above and below the RSIW core. In addition, site 4 was sporadically influenced by high salinity PGIW at depths above 300 m. Sound speed profiles at the site and throughout the western Somali Basin displayed extremely variable microstructure caused by the interleaving of PGIW, SSW, RSIW, and AAIW. Maximum temporal sound speed variability at the site (more than 17 m/sec) occurred at 100 m, just below the depth of the low frequency (91-m) source, and was the greatest such variability encountered at any exercise site. Site 4 was effectively bottom-limited for the high frequency (18-m) source. However, 90-m conjugate depth at the site lay at least 200 m above the corrected bottom, and after 17 March was up to 800 m shallower than the corrected bottom.

(U) Between 22 and 25 March, WILKES collected more than 30 XBTs at a location 20 nm (37 km) northwest of site 4. The predominant upper sound speed minima (at about 500 m) and predominant intermediate sound speed maxima (between 600 and 800 m) were continuous over most of the 78-hour time-series, and generally were associated with the SSW low salinity and RSIW high salinity cores, respectively. Upper minima and intermediate maxima were found to be spatially continuous along several tracks radial to site 4, and probably were continuous throughout much of the western Somali Basin. Half way through the time series, however, the depth of the upper sound speed minimum increased to greater than 600 m, and the intermediate sound speed maximum occurred about 100 m below the depth of the minimum (associated with the AAIW low salinity core). A similar situation occurred along the KINGSPORT 4A1 track (due north of site 4).



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(U) Sound speed structures along the KINGSPORT 4A1 track (between site 4 and Socotra) were even more complex than those at site 4. The entire track was effectively bottom-limited, but at least 200 m deeper than 90-m conjugate depth. At 9°-10°N, the depth of the DSC increased rapidly by about 8.4 m/nm (4.5 m/km). This gradient is the largest found along exercise acoustic tracks and delineates a moderate oceanic frontal zone that extended from the surface to about 2000-m depth. The sonic layer was discontinuous across this front, and intensive mixing within the frontal zone effectively obliterated the double minimum sound speed structure found further to the south. Interleaving of PGIW, SSW, RSIW, and AAIW within the frontal zone is similar to that found throughout the western Somali Basin during the southwest monsoon (Warren et al., 1966). Overall, RSIW was the most important water mass affecting sound speed structures along the 4A1 track. However, mixing of RSIW and AAIW clearly was responsible for much of the complex sound speed microstructure found at site 4 and along tracks radial to it.

(C) Site 5 was located at the southern edge of the Arabian Basin (flanks of the Carlsberg Ridge) and was occupied from 8 to 21 April. All sound speed profiles at the site displayed an upper sound speed minimum (at about 400 m) associated with the SSW low salinity core and an intermediate maximum (at 500-700 m) associated with a strong, preferential flow of RSIW. In addition, site 5 sound speed profiles sporadically displayed a perturbation at the top of the thermocline (30-100 m). The greatest temporal and spatial sound speed variability in the water column (about 15 m/sec) occurred at 150 m, well below the depth of the low frequency (91-m) source. Acoustic propagation at site 5 and along acoustic tracks radial to it was bottom-limited in respect to both the high and low frequency sources.

(C) Site 2 was located on the Owen Ridge (north-northwest of the mouth of the Gulf of Aden) and was occupied during the last week of April. However, the southwest monsoon had not started during the occupation of this site. Although the site was strongly influenced by PGIW and RSIW, neither water mass caused significant upper sound channels, only sound speed microstructure throughout the upper 1500 m of the water column. The greatest temporal and spatial sound speed variability at site 2 (about 5 m/sec) occurred at 100-150 m, and was less than that at any other site except site 3. Acoustic propagation at site 2 and along acoustic tracks radial to it was bottom-limited for both the high (18-m) and low (91-m) frequency CW sources.

(C) Representative sound speed profiles for each exercise site were derived from time-series at the respective site. The site 2 representative profile generally had the highest sound speeds (due to intermixing of RSIW and PGIW), while the site 4 representative profile generally had the lowest sound speeds (primarily due to the effects of SSW and AAIW). In the near-surface layer, however, the site 1A/1B representative profiles had anomalously low sound speeds due to the effects of northeast monsoon upwelling. Representative sound speed profiles for the southwest monsoon (June-September) were derived for each site using historical data and were similar to those for the exercise except above 400-500 m and in regions where upwelling is expected during summer (i.e., sites 2 and 4).

(C) Overall, environmental effects on acoustic propagation and ambient noise were minimal during BEARING STAKE. Except at site 4, propagation at all sites was bottom-limited in respect to both the high frequency (generally 18-m) and low frequency (generally 91-m) sources, and the moderate amounts of sound speed variability encountered should not have caused anomalous propagation patterns. However, the corrected bottom was at least 200 m deeper than 90-m conjugate depth at site 4 and along most acoustic tracks radial to it. This should have allowed for some refraction of downward rays from the low frequency (91-m) source. The intense temporal and spatial sound speed variability throughout the western Somali Basin also should have affected propagation to sensors at site 4, particularly for the low frequency (91-m) source, for which there was some depth excess. Since wind speeds were generally less than 6 m/sec (about 12 knots) and sea/swell heights less than about 3 m (about 10 feet), ambient noise levels above 200 Hz measured during the exercise should have been moderate to low.

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**APPENDIX A**

**SELECTED SOUND SPEED CROSS SECTIONS  
ALONG KINGSPORT SUS AND CW TRACKS (U)**

(C) As part of the BEARING STAKE environmental analysis program, NORDA provided NOSC with sound speed and bathymetric profiles along 27 major acoustic tracks occupied by KINGSPORT. These tracks are listed by site in Table 2. Three of these tracks are extensively discussed in the main body of this report: KINGSPORT track 1A1 (Fig. 6), KINGSPORT track 3A2 (Fig. 9), and KINGSPORT track 4A1 (Fig. 14). The location of these three tracks is shown in Figure 1. Figure 21 shows the location of 10 additional tracks chosen by NOSC for propagation loss modeling. Since these tracks describe spatial sound speed variability throughout much of the northwestern Indian Ocean, they are included herein as Figures 22 through 31. Each track has been previously presented and discussed in the BEARING STAKE Acoustic Assessment Report (NOSC, 1978).

TABLE 2 (U)  
KINGSPORT ACOUSTIC TRACKS WITH  
ANALYZED SOUND SPEED AND BATHYMETRIC PROFILES (U)

| <u>SITE</u> | <u>ACOUSTIC TRACK</u> |                            |
|-------------|-----------------------|----------------------------|
| 1A          | P2                    | <u>S1</u> 1A1              |
| 1B          | <u>S1</u>             | P5                         |
| 2           | <u>P1</u>             | S1 <u>P3a</u> <u>P3</u>    |
| 3           | S1                    | S2 <u>P2</u> <u>P4</u> 3A2 |
| 4           | <u>P1</u>             | S1 P2 P3 <u>P5</u> 4A1     |
| 5           | S1                    | <u>P1</u> <u>P5</u>        |

LEGEND:  
P = CW Projection  
S = SUS  
A = Aircraft Sus  
     = Sound speed cross-section  
    = Contained herein

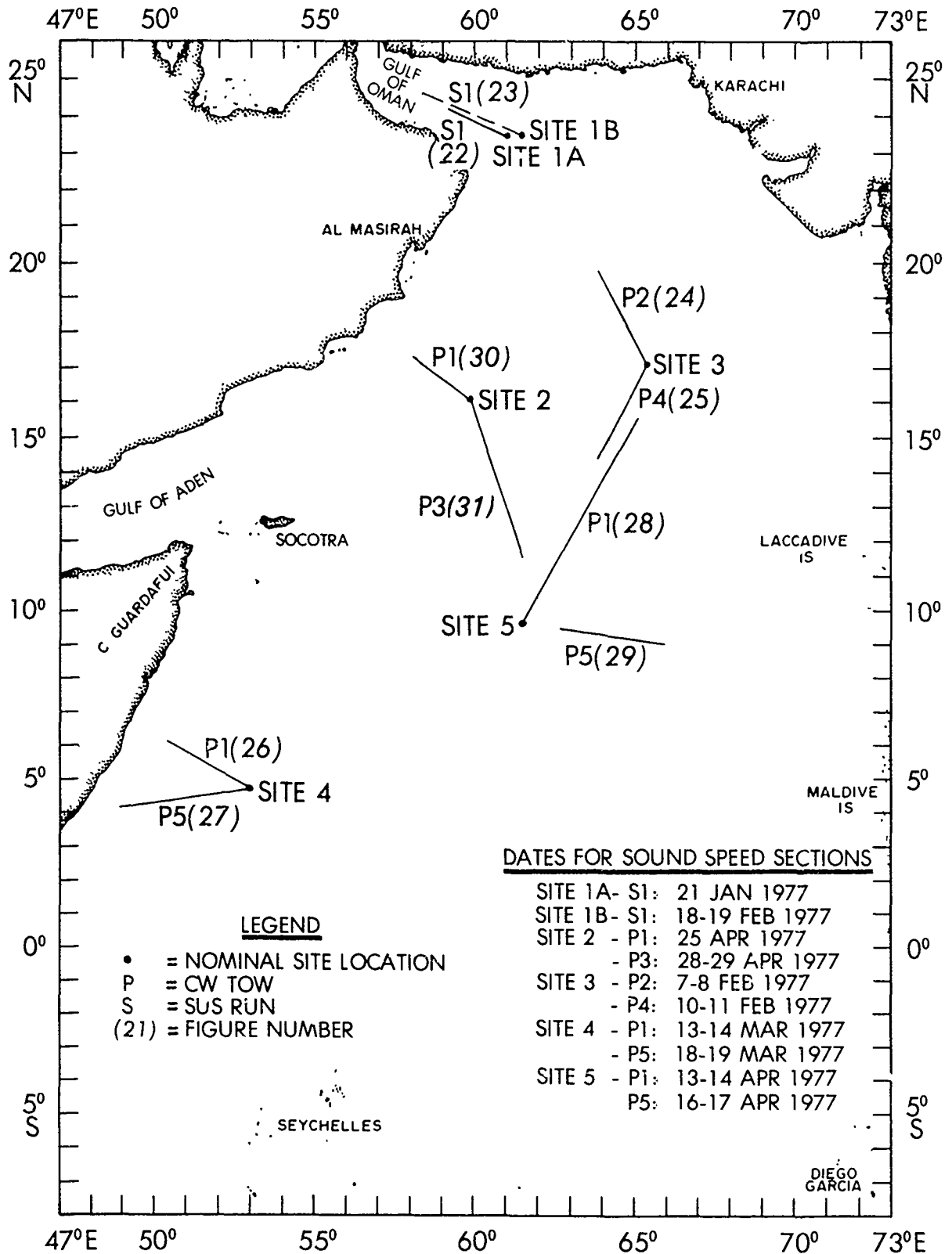


Figure 21.(C) Location of selected sound speed sections along KINGSPORT SUS and CW tracks (U)

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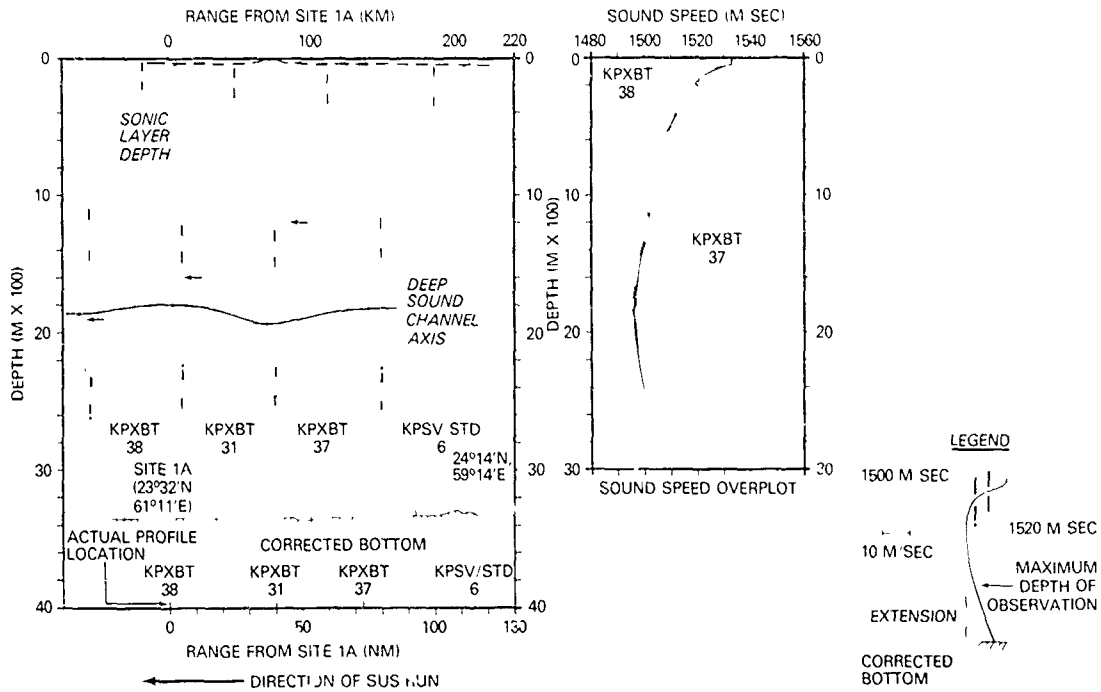


Figure 22.(C) Sound speed structure along KINGSFORT S1 track at site 1A (U)

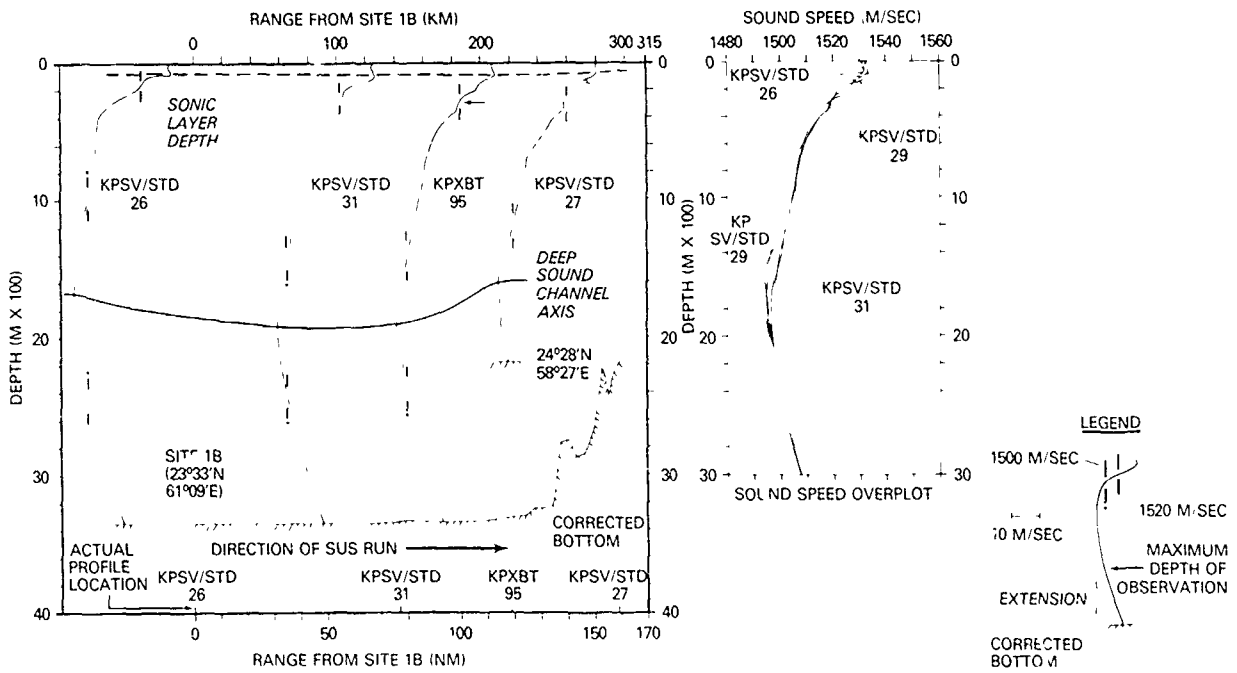


Figure 23.(C) Sound speed structure along KINGSFORT S1 track at site 1B (U)

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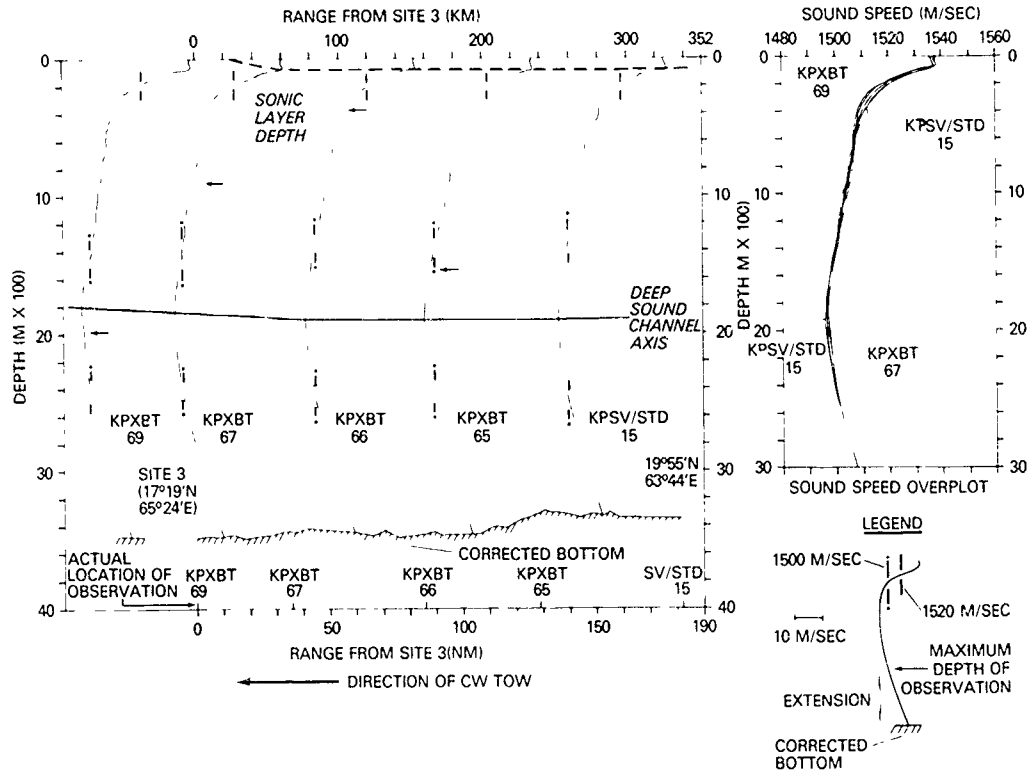


Figure 24.(C) Sound speed structure along KINGSFORT P2 track at site 3 (U)

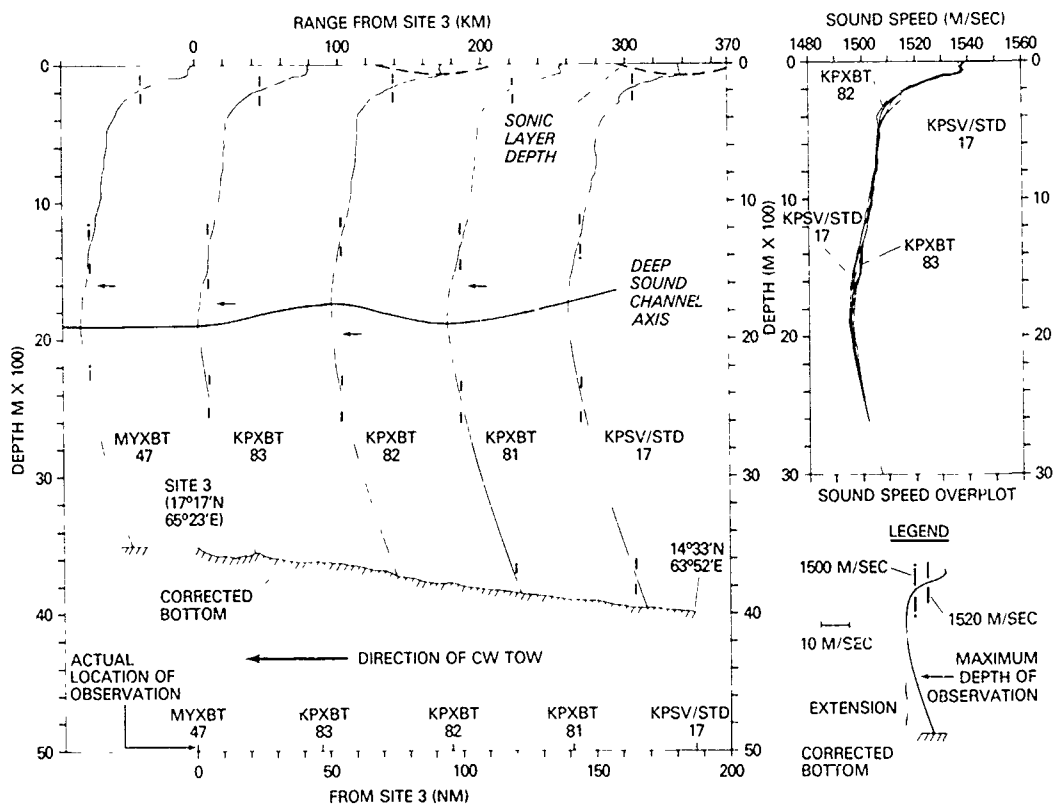


Figure 25(C) Sound speed structure along KINGSFORT P4 track at site 3 (U)



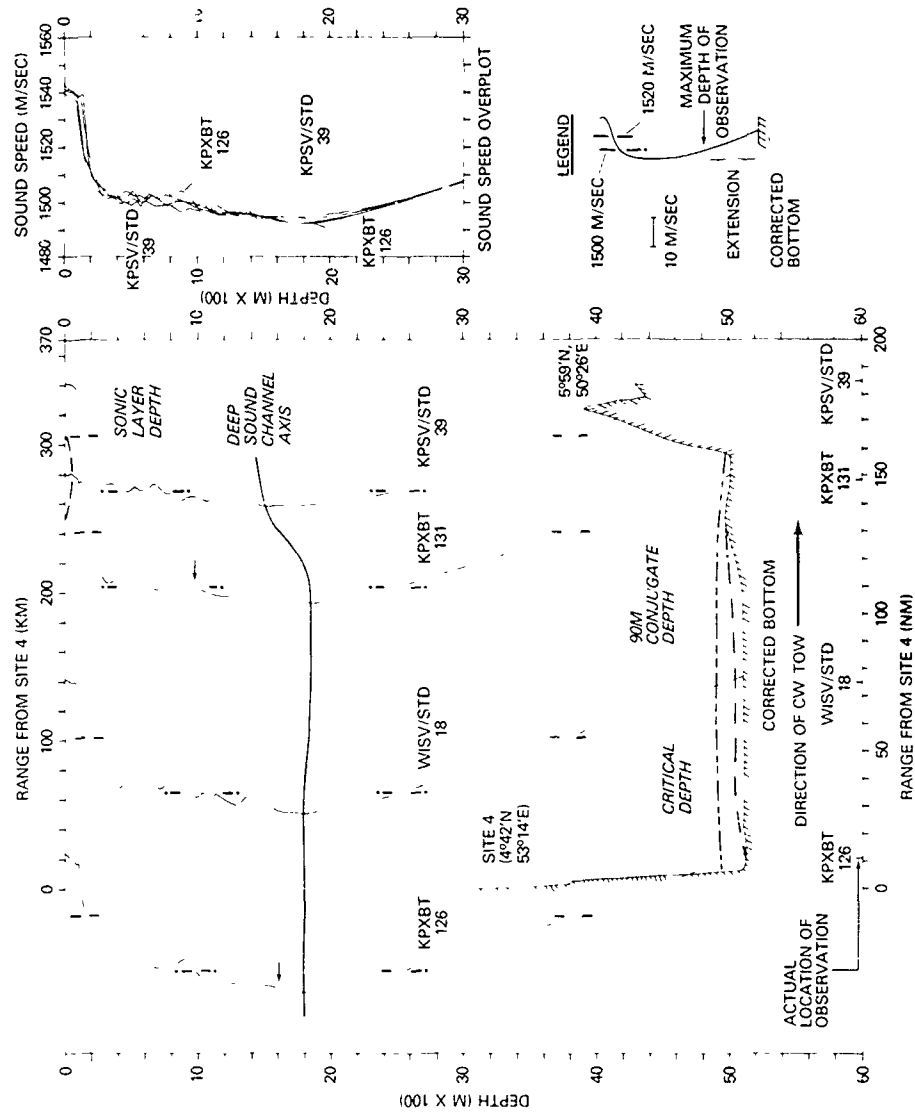


Figure 26.(C) Sound speed structure along KINGSPORT PI track at site 4 (U)

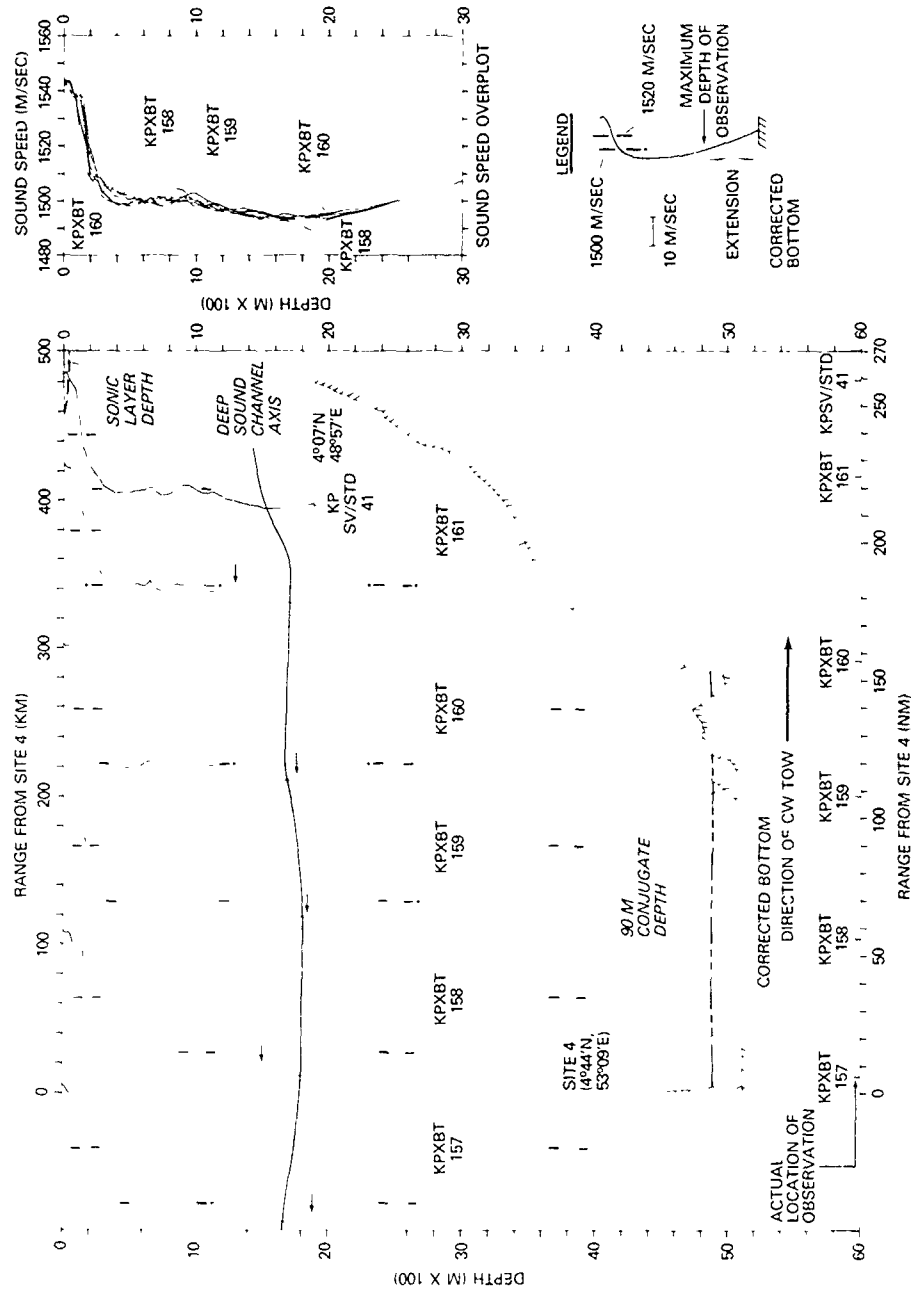


Figure 27.(C) Sound speed structure along KINGSPORT P5 track at site 4 (U)

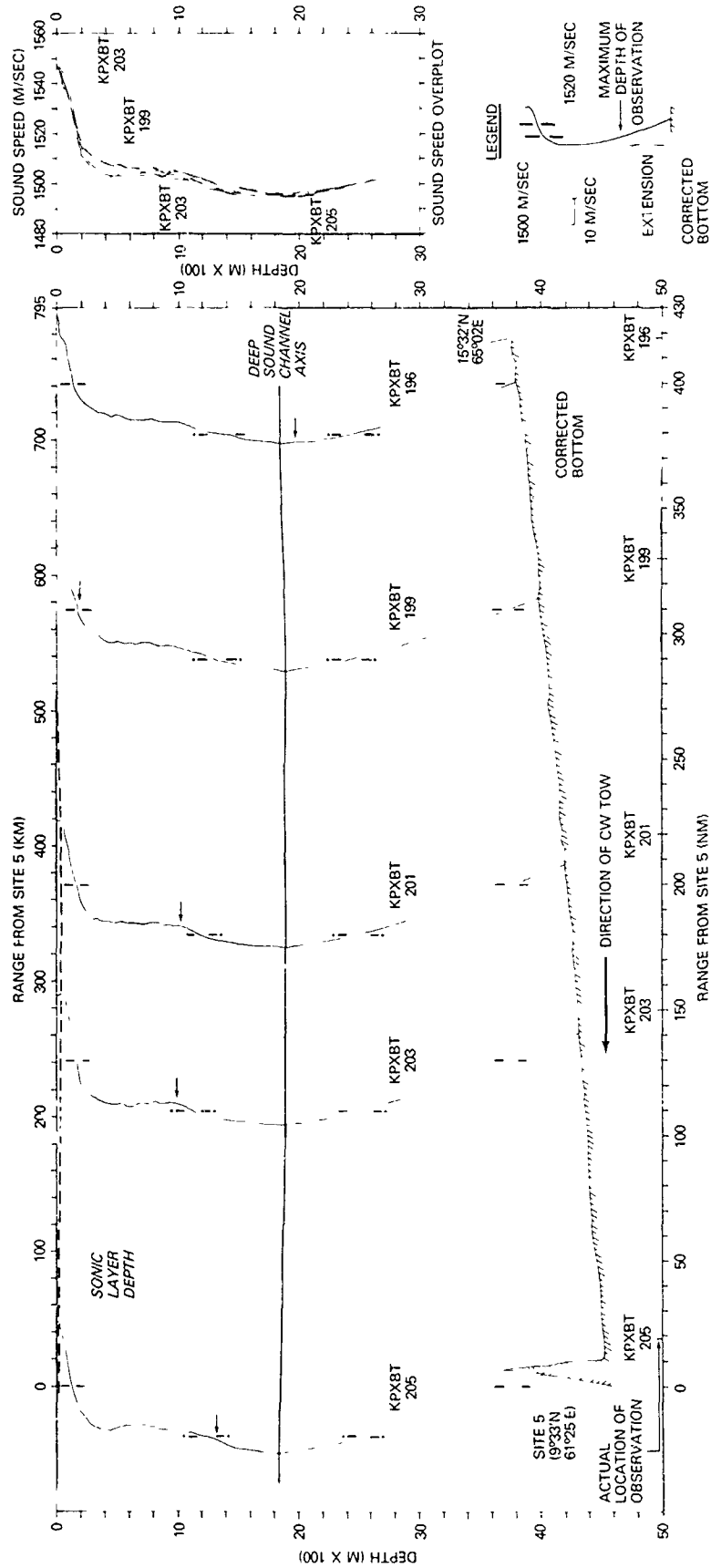


Figure 28.(C) Sound speed structure along KINGSPORT P1 track at site 5 (U)

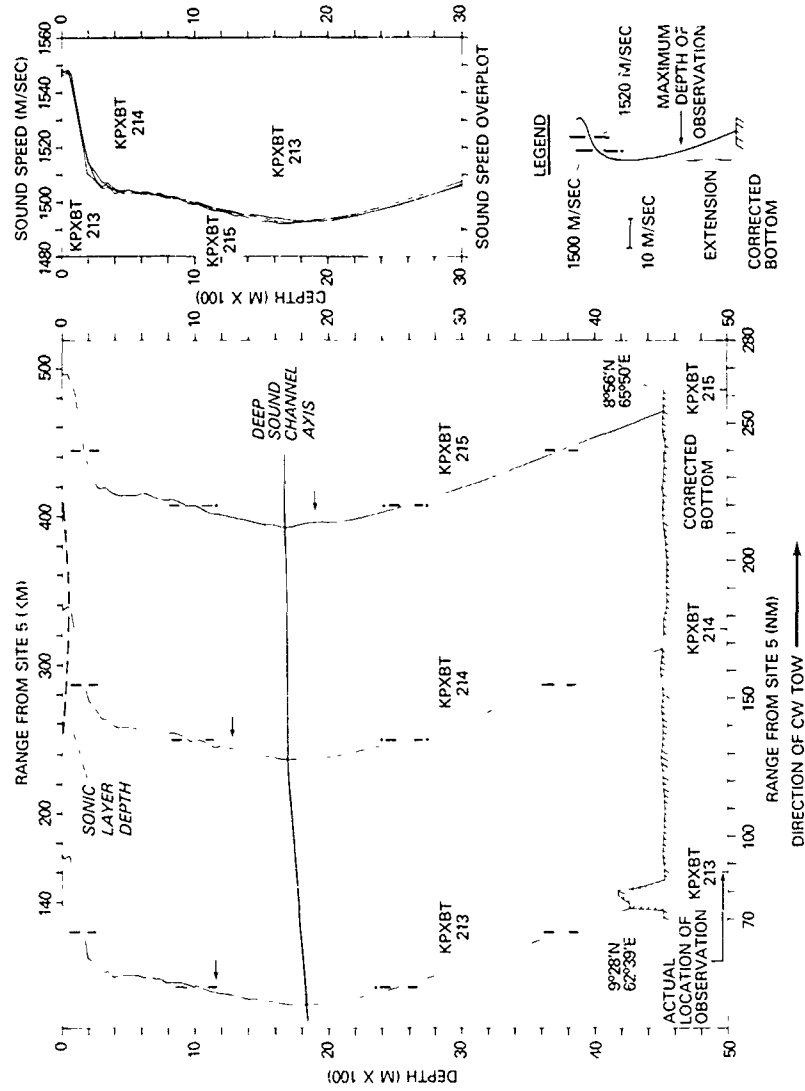


Figure 29.(C) Sound speed structure along KINGSPORT P5 track at site 5 (U)

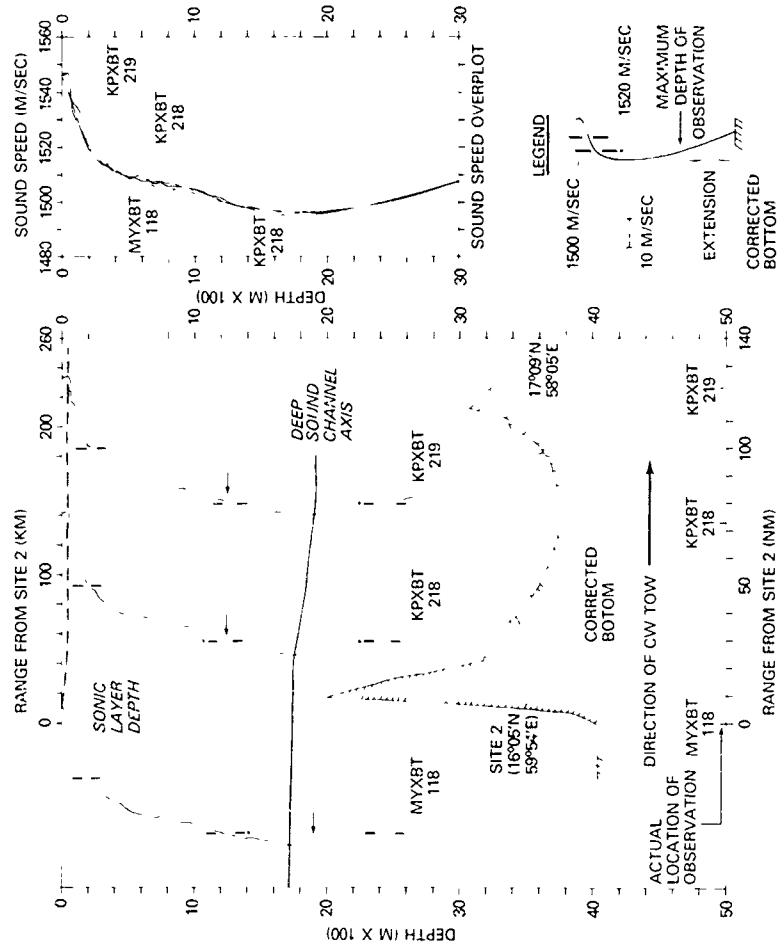


Figure 30.(C) Sound speed structure along KINGSFORT P1 track at site 2 (U)

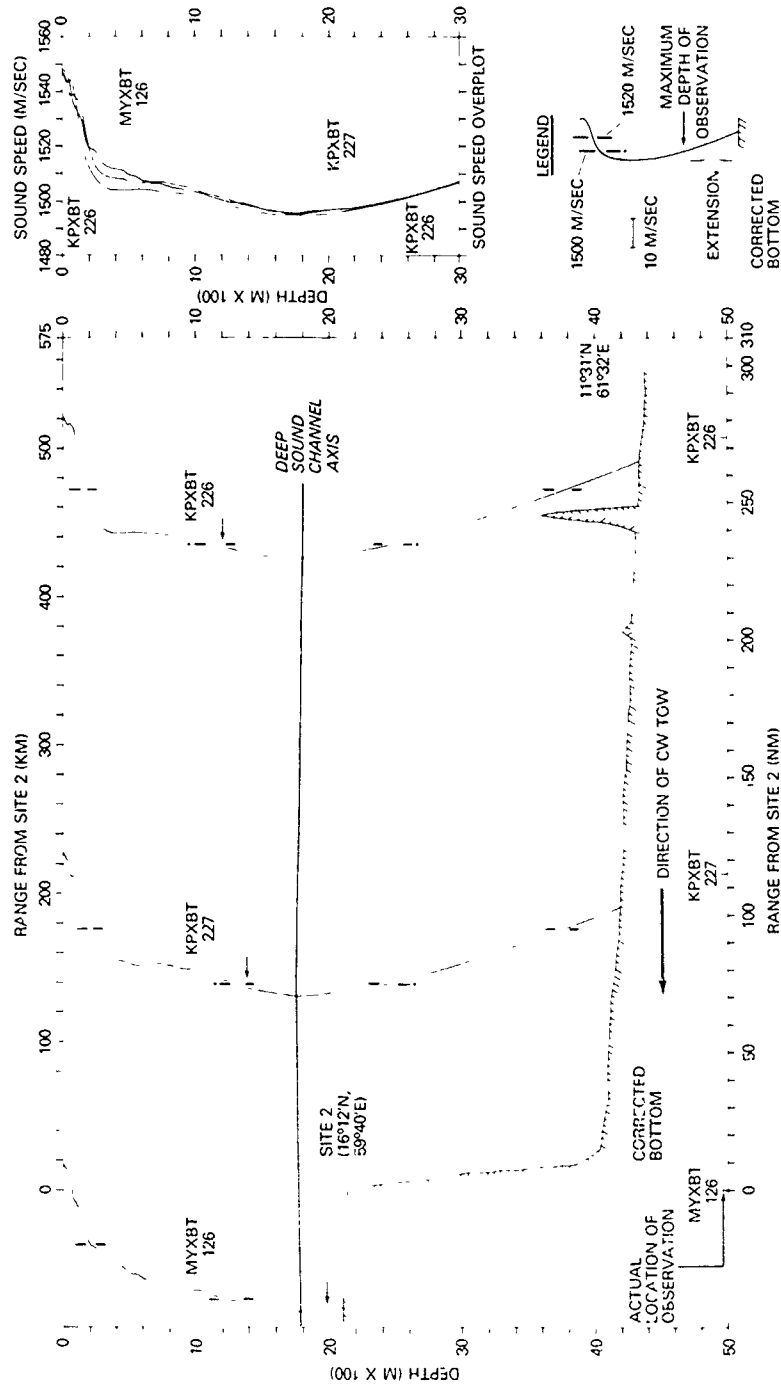


Figure 31.(C) Sound speed structure along KINGSFORT P3 track at site 2 (U)

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**APPENDIX B****REPRESENTATIVE EXERCISE AND SOUTHWEST MONSOON SOUND SPEED PROFILES (U)**

(U) Representative sound speed profiles were chosen at each BEARING STAKE site for both the period of site occupation and for the southwest monsoon (June-September). These profiles are presented graphically in the main body of this report in Figure 20. Listings of the profiles are given in Table 3 (sites 1A and 1B), Table 4 (sites 3 and 4), and Table 5 (sites 5 and 2). Representative exercise profiles were derived from time-series of sound speed at each site, and are near-model profiles. Those for sites 1A/1B and 3 are from the northeast monsoon. Those from sites 4, 5, and 2 are from the transitional period between the northeast and southwest monsoons. Representative southwest monsoon sound speed profiles for each site were chosen from historical data collected as part of the International Indian Ocean Expedition.



TABLE 3(U)

REPRESENTATIVE EXERCISE AND SOUTHWEST MONSOON  
SOUND SPEED PROFILES FOR SITES 1A AND 1B(U)

| EXERCISE (Site 1A) |               | EXERCISE (Site 1B) |               | S. W. MONSOON |               |
|--------------------|---------------|--------------------|---------------|---------------|---------------|
| Depth<br>(m)       | SS<br>(m/sec) | Depth<br>(m)       | SS<br>(m/sec) | Depth<br>(m)  | SS<br>(m/sec) |
| 0                  | 1533.0        | 0                  | 1531.9        | 0             | 1542.5 SLD    |
| 25                 | 1533.1        | 10                 | 1532.0 SLD    | 10            | 1542.3        |
| 65                 | 1533.3 SLD    | 25                 | 1530.9        | 20            | 1542.3        |
| 100                | 1521.1        | 50                 | 1530.8        | 30            | 1530.6        |
| 125                | 1519.8        | 75                 | 1522.4        | 50            | 1528.6        |
| 150                | 1518.7        | 100                | 1520.4        | 75            | 1526.5        |
| 165                | 1517.9        | 150                | 1519.1        | 100           | 1523.6        |
| 185                | 1518.5        | 200                | 1517.7        | 125           | 1523.0        |
| 200                | 1517.6        | 250                | 1514.0        | 150           | 1522.0        |
| 250                | 1514.4        | 300                | 1509.5        | 200           | 1519.8        |
| 300                | 1513.2        | 350                | 1507.4        | 250           | 1515.0        |
| 350                | 1510.9        | 400                | 1506.0        | 300           | 1511.0        |
| 400                | 1509.7        | 500                | 1504.8        | 400           | 1506.6        |
| 501                | 1506.7        | 550                | 1504.5        | 500           | 1506.1        |
| 600                | 1505.4        | 575                | 1504.6        | 600           | 1505.0        |
| 700                | 1504.6        | 625                | 1504.0        | 700           | 1504.5        |
| 800                | 1503.9        | 675                | 1503.6        | 800           | 1503.6        |
| 900                | 1502.6        | 700                | 1503.7        | 900           | 1502.6        |
| 1000               | 1501.7        | 800                | 1502.6        | 1000          | 1501.6        |
| 1100               | 1500.3        | 900                | 1501.9        | 1100          | 1500.3        |
| 1150               | 1499.2        | 1000               | 1500.5        | 1200          | 1499.1        |
| 1200               | 1499.1        | 1100               | 1499.1        | 1300          | 1497.8        |
| 1300               | 1498.3        | 1200               | 1498.6        | 1400          | 1496.9        |
| 1400               | 1497.1        | 1300               | 1497.7        | 1500          | 1496.1        |
| 1500               | 1496.3        | 1400               | 1496.8        | 1750          | 1495.6 DSC    |
| 1600               | 1495.6        | 1500               | 1495.9        | 2000          | 1496.0        |
| 1750               | 1495.4 DSC    | 1500               | 1495.3        | 2500          | 1500.6        |
| 1825               | 1495.6        | 1725               | 1495.0 DSC    | 3000          | 1507.8        |
| 1900               | 1495.8        | 1800               | 1495.3        | 3350          | 1513.3 CBD    |
| 2000               | 1496.3        | 1901               | 1495.2        |               |               |
| 2200               | 1497.8        | 2000               | 1495.7        |               |               |
| 2500               | 1500.7        | 2200               | 1497.2        |               |               |
| 3000               | 1507.7        | 2500               | 1500.3        |               |               |
| 3350               | 1513.3 CBD    | 3000               | 1507.7        |               |               |
|                    |               | 3350               | 1513.5 CBD    |               |               |

ABBREVIATIONS:

- SLD = Sonic Layer Depth
- DSC = Deep Sound Channel
- CBD = Corrected Bottom Depth

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TABLE 4(U)

REPRESENTATIVE EXERCISE AND SOUTHWEST MONSOON  
SOUND SPEED PROFILES FOR SITES 3 AND 4(U)

| SITE 3       |               |               |               | SITE 4       |               |               |               |
|--------------|---------------|---------------|---------------|--------------|---------------|---------------|---------------|
| EXERCISE     |               | S. W. MONSOON |               | EXERCISE     |               | S. W. MONSOON |               |
| Depth<br>(m) | SS<br>(m/sec) | Depth<br>(m)  | SS<br>(m/sec) | Depth<br>(m) | SS<br>(m/sec) | Depth<br>(m)  | SS<br>(m/sec) |
| 0            | 1538.5        | 0             | 1543.6        | 0            | 1543.9 SLD    | 0             | 1528.1 SLD    |
| 35           | 1538.9 SLD    | 10            | 1543.8        | 25           | 1543.0        | 10            | 1527.6        |
| 50           | 1537.8        | 20            | 1544.0        | 50           | 1541.0        | 20            | 1527.6        |
| 75           | 1537.2        | 30            | 1544.1        | 75           | 1532.9        | 30            | 1527.6        |
| 100          | 1529.5        | 50            | 1544.5 SLD    | 100          | 1528.2        | 50            | 1527.3        |
| 150          | 1521.7        | 75            | 1536.0        | 160          | 1518.2        | 75            | 1526.5        |
| 200          | 1515.9        | 100           | 1532.5        | 201          | 1514.3        | 100           | 1526.3        |
| 250          | 1512.7        | 125           | 1529.1        | 250          | 1509.4        | 125           | 1522.1        |
| 300          | 1511.1        | 200           | 1519.6        | 300          | 1505.1        | 150           | 1511.1        |
| 350          | 1509.3        | 250           | 1516.3        | 400          | 1499.8        | 200           | 1505.0        |
| 400          | 1507.9        | 300           | 1512.1        | 450          | 1498.9        | 250           | 1503.5        |
| 480          | 1506.9        | 400           | 1509.0        | 500          | 1500.5        | 300           | 1501.5        |
| 500          | 1507.0        | 500           | 1507.3        | 575          | 1501.9        | 400           | 1499.5        |
| 540          | 1506.4        | 600           | 1506.6        | 600          | 1501.4        | 500           | 1499.3        |
| 560          | 1506.7        | 700           | 1506.0        | 625          | 1502.4        | 600           | 1501.8        |
| 600          | 1506.2        | 800           | 1505.1        | 675          | 1499.6        | 700           | 1497.6        |
| 630          | 1506.4        | 900           | 1504.5        | 726          | 1500.7        | 800           | 1497.1        |
| 701          | 1505.5        | 1000          | 1504.0        | 799          | 1498.9        | 900           | 1496.8        |
| 800          | 1504.8        | 1100          | 1502.1        | 849          | 1500.1        | 1000          | 1496.1        |
| 900          | 1504.3        | 1200          | 1501.3        | 874          | 1499.1        | 1100          | 1495.8        |
| 1000         | 1503.1        | 1300          | 1500.0        | 925          | 1499.3        | 1200          | 1496.3        |
| 1100         | 1502.6        | 1400          | 1498.8        | 999          | 1498.4        | 1300          | 1496.0        |
| 1200         | 1501.9        | 1500          | 1497.8        | 1098         | 1497.2        | 1400          | 1495.3        |
| 1300         | 1500.9        | 1750          | 1495.8 DSC    | 1197         | 1496.1        | 1500          | 1494.8        |
| 1400         | 1500.0        | 2000          | 1496.2        | 1297         | 1495.6        | 1750          | 1493.0 DSC    |
| 1500         | 1499.2        | 2500          | 1500.6        | 1346         | 1495.9        | 2000          | 1494.6        |
| 1600         | 1498.3        | 3000          | 1507.7        | 1421         | 1494.2        | 2500          | 1500.3        |
| 1700         | 1497.8        | 3580          | 1516.9 CBD    | 1470         | 1494.6        | 3000          | 1507.5        |
| 1801         | 1497.1        |               |               | 1595         | 1492.4        | 4000          | 1523.6        |
| 1890         | 1496.9 DSC    |               |               | 1743         | 1492.3 DSC    | 5106          | 1542.8 CBD    |
| 2001         | 1497.2        |               |               | 1892         | 1493.2        |               |               |
| 2200         | 1498.5        |               |               | 1991         | 1494.1        |               |               |
| 2500         | 1501.3        |               |               | 2189         | 1495.8        |               |               |
| 3001         | 1507.6        |               |               | 2511         | 1500.1        |               |               |
| 3580         | 1516.8 CBD    |               |               | 3004         | 1507.3        |               |               |
|              |               |               |               | 3498         | 1515.2        |               |               |
|              |               |               |               | 4012         | 1523.5        |               |               |
|              |               |               |               | 4501         | 1531.4        |               |               |
|              |               |               |               | 5106         | 1542.5 CBD    |               |               |

ABBREVIATIONS:

Same as previous table

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TABLE 5 (U)

REPRESENTATIVE EXERCISE AND SOUTHWEST MONSOON  
SOUND SPEED PROFILES FOR SITES 5 AND 2 (U)

| SITE 5       |               |               |               | SITE 2       |               |               |               |
|--------------|---------------|---------------|---------------|--------------|---------------|---------------|---------------|
| EXERCISE     |               | S. W. MONSOON |               | EXERCISE     |               | S. W. MONSOON |               |
| Depth<br>(m) | SS<br>(m/sec) | Depth<br>(m)  | SS<br>(m/sec) | Depth<br>(m) | SS<br>(m/sec) | Depth<br>(m)  | SS<br>(m/sec) |
| 0            | 1545.5 SLD    | 0             | 1540.3        | 0            | 1546.7 SLD    | 0             | 1536.8        |
| 30           | 1539.5        | 10            | 1540.5        | 25           | 1544.4        | 10            | 1537.0        |
| 50           | 1542.1        | 20            | 1540.6        | 50           | 1540.0        | 20            | 1537.0        |
| 75           | 1540.0        | 30            | 1540.8        | 75           | 1537.4        | 30            | 1537.1 SLD    |
| 100          | 1526.3        | 50            | 1541.1        | 100          | 1534.6        | 50            | 1536.6        |
| 150          | 1514.6        | 75            | 1541.3 SLD    | 150          | 1526.7        | 75            | 1534.1        |
| 200          | 1509.3        | 100           | 1540.6        | 200          | 1520.3        | 100           | 1530.6        |
| 250          | 1504.9        | 125           | 1535.8        | 250          | 1517.1        | 125           | 1526.3        |
| 301          | 1502.7        | 150           | 1529.5        | 270          | 1517.3        | 150           | 1522.1        |
| 350          | 1501.9        | 200           | 1513.5        | 300          | 1513.6        | 200           | 1515.3        |
| 400          | 1501.8        | 250           | 1508.0        | 350          | 1512.6        | 250           | 1511.8        |
| 450          | 1501.6        | 300           | 1504.5        | 410          | 1510.7        | 300           | 1509.1        |
| 500          | 1502.7        | 400           | 1503.0        | 440          | 1510.9        | 400           | 1506.8        |
| 550          | 1503.2        | 500           | 1502.1        | 480          | 1510.2        | 500           | 1505.6        |
| 649          | 1503.6        | 600           | 1502.5        | 530          | 1508.2        | 600           | 1505.5        |
| 699          | 1503.4        | 700           | 1501.3        | 560          | 1508.4        | 700           | 1505.1        |
| 800          | 1501.9        | 800           | 1500.1        | 620          | 1507.6        | 800           | 1504.6        |
| 824          | 1502.2        | 900           | 1498.8        | 660          | 1507.6        | 900           | 1503.5        |
| 900          | 1501.4        | 1000          | 1497.6        | 710          | 1506.8        | 1000          | 1502.5        |
| 1000         | 1500.0        | 1100          | 1496.8        | 750          | 1507.0        | 1100          | 1501.5        |
| 1098         | 1499.1        | 1200          | 1496.1        | 800          | 1505.8        | 1200          | 1500.5        |
| 1198         | 1498.1        | 1300          | 1495.5        | 850          | 1505.6        | 1300          | 1499.5        |
| 1296         | 1497.5        | 1400          | 1494.6        | 900          | 1505.0        | 1400          | 1498.1        |
| 1396         | 1496.4        | 1500          | 1494.1        | 950          | 1504.9        | 1500          | 1497.1        |
| 1495         | 1495.2        | 1750          | 1493.3 DSC    | 1010         | 1503.9        | 1750          | 1495.6 DSC    |
| 1594         | 1494.7        | 2000          | 1494.1        | 1040         | 1504.2        | 2000          | 1496.1        |
| 1693         | 1494.4        | 2500          | 1499.8        | 1100         | 1502.7        | 2500          | 1500.5        |
| 1768         | 1494.3 DSC    | 3000          | 1507.5        | 1200         | 1501.4        | 3100          | 1509.0 CBD    |
| 1893         | 1494.6        | 3909          | 1522.5 CBD    | 1300         | 1500.3        |               |               |
| 1991         | 1495.1        |               |               | 1400         | 1499.2        |               |               |
| 2189         | 1496.3        |               |               | 1540         | 1497.1        |               |               |
| 2511         | 1499.9        |               |               | 1600         | 1497.4        |               |               |
| 3003         | 1506.9        |               |               | 1720         | 1496.3        |               |               |
| 3495         | 1515.1        |               |               | 1780         | 1496.6        |               |               |
| 3909         | 1522.5 CBD    |               |               | 1820         | 1496.2 DSC    |               |               |
|              |               |               |               | 1900         | 1496.6        |               |               |
|              |               |               |               | 1980         | 1497.1        |               |               |
|              |               |               |               | 2200         | 1498.0        |               |               |
|              |               |               |               | 2500         | 1500.3        |               |               |
|              |               |               |               | 3100         | 1509.1 CBD    |               |               |

ABBREVIATIONS:  
Same as previous table

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APPENDIX C

LIST OF ACRONYMS AND ABBREVIATIONS (U)

- AAIW - Antarctic Intermediate Water; a cold, low salinity water mass formed in the vicinity of the Antarctic Circumpolar Convergence
- BIW - Banda Intermediate Water; a cool, low salinity water mass formed in the Banda Sea of the Indonesian Archipelago
- BMA - Bottom Mounted Array; an acoustic measuring device
- C. - cape
- °C - degrees Centigrade
- CW - continuous wave; a type of acoustic projector
- DI - HMAS DIAMANTINA
- DSC - deep sound channel; the absolute sound speed minimum
- E - East longitude
- Hz - Hertz
- Is. - island
- km - kilometer(s)
- KP - USNS KINGSPORT
- m - meter(s)
- m/sec - meters-per-second
- MY - USNS MYER
- MZ - USNS MIZAR
- N - North latitude
- nm - nautical mile(s)
- NORDA - Naval Ocean Research and Development Activity, NSTL Station, Mississippi
- NOSC - Naval Ocean Systems Center, San Diego, California
- NSTL - National Space Technology Laboratories
- PGIW - Persian Gulf Intermediate Water; a warm, high salinity water mass formed in the Persian Gulf
- RSIW - Red Sea Intermediate Water; a warm, high salinity water mass formed in the Red Sea
- S - South latitude
- SSW - Subtropical Subsurface Water; a cool, low salinity water mass formed along the Subtropical Convergence
- SUS - signal-underwater-sound; an acoustic depth charge
- SV/STD - sound velocity-salinity-temperature-depth; an oceanographic instrument that measures sound speed, temperature, and salinity as a function of pressure or depth
- T-S - temperature-salinity
- XBT - shipboard expendable bathythermograph; an oceanographic instrument that measures temperature as a function of depth to either 460 m (Sippican Model T-4 probe), 760 m (T-7 probe), or 1830 m (T-5 probe)
- Z - Zulu or Greenwich Mean Time
- ‰ - parts-per-thousand

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excess occurred for the low frequency source. At site 4 and throughout the western Somali Basin, interleaving of intrusive water masses (including Red Sea and Antarctic Intermediate Waters) caused complex and highly variable sound speed profiles to depths of at least 1800 m. At site 1B (Gulf of Oman) sound speed profiles were up to 5 m/sec lower than those observed one month earlier (site 1A), probably due to increased northeast monsoon upwelling after the site 1 occupation. Maximum temporal and spatial sound speed variability throughout the exercise area occurred between about 100 and 150 m, just below the depth of the low frequency source. At all sites, wind speeds and sea/swell heights were low to moderate and should not have markedly influenced ambient noise levels above 200 Hz.

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