the net integration (like a realistic eddy-induced anomaly would), but when they are near either boundary, they alter the final value, often dramatically (like a boundary current would), contributing to the spottiness of Fig. 1. Thus the sharp peak at 8.5°N in January (Fig. 1b and 1d) is spurious: it is caused by unrealistic salinities near 750 m at the eastern boundary.

Conclusions

This note illustrates why existing climatologies do not, in their present state, resolve the BHT and its seasonal cycle properly. It is necessary to understand better which differences in data bases or averaging techniques are responsible for the differences in the final data sets, and at least LEV82 and LEV94 need to be carefully scrutinised in order to eliminate, especially near the extremities of the sections, the unrealistic anomalies that passed quality control. The often very different results obtained from various climatologies are of concern for modelling purposes, because regional models often impose climatological fields in sponge layers, which amounts to imposing a climatological BHT there. A more complete discussion will be presented in a longer manuscript in preparation.

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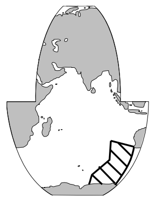
Deep Circulation Southwest of Australia



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Deep water colder than θ = 1.0°C is found (Mantyla and Reid, 1995) in the subtropical/tropical Central Indian Basin (CIB), and all evidence points to its source as the South Australian Basin (SAB). The gap between Broken Ridge and Naturaliste Plateau (Fig. 1) is one passage for exchange between the SAB and the northern basins, allowing flow through the Perth and West Australian Basins, with leaks from the latter through the Ninety East Ridge into the CIB. Another pathway takes somewhat warmer deep water from the SAB directly into the CIB over the deep sills of the ridge connecting the Broken Ridge to the Southeast Indian Ridge, (see Talley and Baringer, 1995). The Australian-Antarctic Basin (AAB) is in turn the source of deep waters in the SAB, and the Southeast Indian Ridge separates the SAB and AAB with a sill depth of about 3500 m in the Antarctic Discordance Zone.

WHP sections I8S/I9S, December 1994 through mid-January 1995 provided two crossings of the Southern Ocean between the southern coast of Australia and the Adelie coast of Antarctica (Fig. 1). The I8S/I9S sections were designed to examine the interior gyral circulation of the AAB as well as the Deep Western Boundary Current (DWBC), Speer and Forbes (1994), flowing northwards along the eastern flank of the Kerguelen Plateau, and the Princess Elisabeth Trough (PET) separating the Plateau from Antarctica that allows exchange between the SAB and the Weddell Gyre. The sections in the SAB were designed to define the circulation carrying deep waters

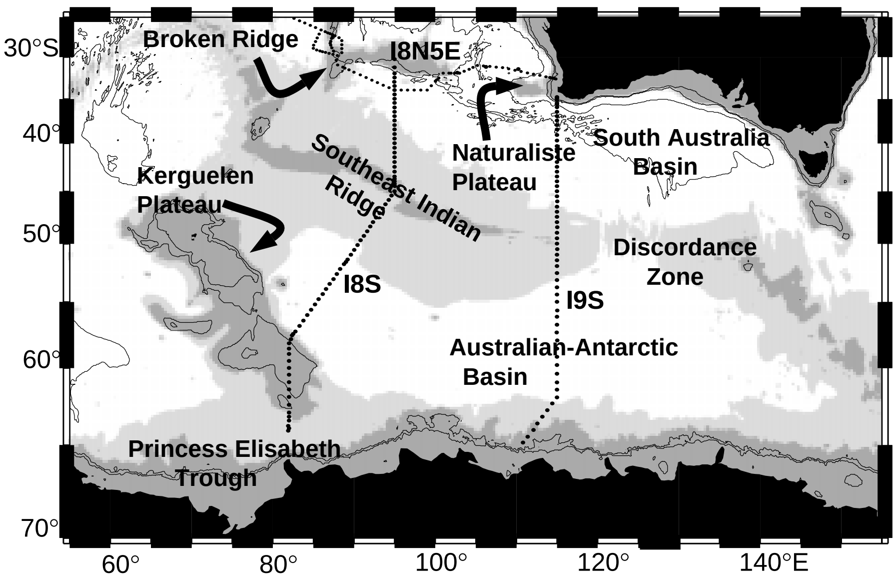

Figure 1. Bathymetric chart of South Australia and Australian-Antarctic Basins, depths less than 3000 m. are shaded dark grey, and less than 4000 m. light grey. Filled circles indicate the station positions of WHP segments I8S, I9S and I8N/5E (the last discussed by Talley and Baringer, 1995).

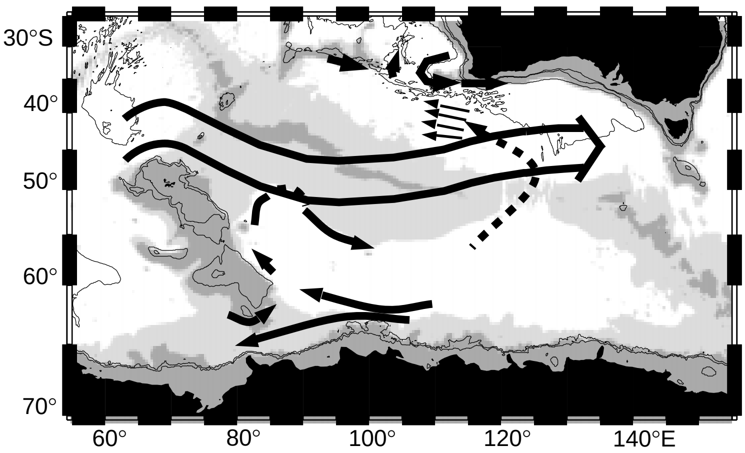

Figure 2. Summary circulation scheme based on preliminary I8S/I9S analysis.

towards the CIB. Fig. 2 gives a summary circulation scheme from our preliminary analysis. We produce a tentative, qualitative circulation scheme for some elements of the overall northward movement of cold deep water through the gyral flows in the SAB and AAB.

The origins of the DWBC off Kerguelen Plateau

I8S extended from Broken Ridge across the Southeast Indian Ridge, to Kerguelen Plateau and into the PET as far as the ice edge. The potential temperature contours are shown in Fig. 3a (page 24). A strong shear signature through stations 64-68 denotes the DWBC along the flank of Kerguelen Plateau, near where it was first reported by Speer and Forbes (1994) as having a transport of $6 \times 10^6 m^3 sec^{-1}$ following the contour of the Plateau. Stations 68–69 define a shear reversal as the section reaches the plateau top. Crossing the Plateau, isotherms descend well into the PET before rising steeply to the ice edge in the southern PET. That rise is the shear signature for westward flow through the PET similar to that reported by Speer and Forbes (1994) and Frew *et al.* (1995). They suggest that the westward flow precludes Weddell influence on the AAB by flow through the PET.

In the northern PET our section suggests eastward flow, which would bring Weddell Gyre waters into the AAB. The DWBC has a monotonic shear signature except for the reversal over the shallower part of the Plateau. The deep property scatter plots show onshore–offshore transitions across the DWBC and a vertical layering of the water masses. Fig. 4a shows one scatter plot example, θ-silica. I8S stations 55–69 span the DWBC and adjacent waters, with stations 65–67 lying in the core of the current. In the deep water the DWBC core stations are consistently slightly lower (order 2μmol/kg) in silica at a given temperature than offshore; we show this on Fig. 4a by two average curves. The only exception is station 67 on the inshore edge of the core, where the silica transitions to being higher than the waters in the rest of the core and offshore, for temperatures 0.1°C–0.3°C. Inshore of station 68, the silica levels systematically rise. High silica levels are found over the southern Kerguelen Plateau, and we indicate with a closed curve on the figure these warmer high silica waters. Most importantly, we find waters similar to those at stations 67–68 in the northern PET where the shear suggests eastward flow, and where the coldest water is 0.1°C. So we conclude that eastward flow of high silica waters from the Weddell through the PET occurs at temperatures above 0.1°C, and follows the Kerguelen Plateau contours to contribute to the northward flow of the DWBC. As we will see below, there seems to be no source internal to the AAB for these elevated silica values.

DWBC waters colder than 0.1˚C show lower silica than the waters offshore, Fig. 4b. Stations 67–68 have maximum differential and distinct silica minima near θ = -0.35°C. Low silica in the temperature range -0.3°C to -0.4°C is a general feature of deep waters near Antarctica. It stems from the plumes of dense, nutrient depleted water deep water formed near shelves that even after entrainment show nutrient minima far downstream, *e.g.* Carmack (1973). Waters this cold are not found in the eastward flow regime in the northern PET – and in any case, the interior waters of the Weddell have too high silica to be a plausible source of silica this low, *e.g.* Mantyla and Reid (1995, Fig. 2e). Our section in the PET does not extend far enough up the Antarctic continental slope to sample the westward flow regime. The part we did sample shows a more extreme silica minimum for the same temperature range as the DWBC, Fig. 4c. We attribute both these minima to the westward flow along the southern flank of the AAB, which was much better sampled in I9S, Fig. 2b. There, a more extreme silica minimum is found at the same temperature in the westward flow along the continental slope, most extreme in the south, less extreme in the north, Fig. 4c. Our second conclusion is the westward deep flow along the Antarctic continental slope, with ultimate origins in deep water formed in the Ross Sea and the Adelie coast, bifurcates in the southwestern AAB to supply both continued westward flow through the PET into the Weddell–Enderby Basin and a northward branch into the DWBC flow off the Kerguelen Plateau. This branch is the sole source for northward DWBC flow for θ<0.1°C, but for θ>0.1°C the northward branching waters converge with the eastward flow of Weddell waters from the northern PET as a combined source for DWBC flow.

Orsi and Bullister (1996) map CFC-11 on two surfaces close to our demarcation of 0.1°C. On both surfaces the CFC-11 picture mirrors the classical tracer fields, with the influence of the westward flow along the continental slope in the southern AAB (low silicate, phosphate and nitrate, and elevated oxygen) correlated with higher CFC-11, and feeding a northward extension in the DWBC and continued westward flow through the southern PET. Our eastward flow regime in the northern PET, and its northward extension as the inshore part of the DWBC (high silicate, phosphate and nitrate, and low oxygen) show as lowered CFC-11. The overall circulation geometry leads to the westward flow regime providing isolated property extrema within the DWBC (low silicate, phosphate and nitrate, and elevated oxygen and CFC-11), with Weddell Waters from the PET to the west and AAB gyre interior waters to the east.

The bifurcation of the westward flow along the continental slope suggests a dividing streamline somewhere across the continental slope of the I9S section. North of this, the westward flow supplies the northward branch into the DWBC, south of it the waters continue westward through the PET to the Weddell. The dividing streamline may be at different positions along the I9S section for different temperatures. For a minimal mixing interpretation, producing the northern limit for the dividing streamline, we look along the I9S section for the θ-Si relation closest to the "Inner core" DWBC curve on Fig. 4c, yielding station 92, Fig. 4d. The transition from silica distinctly higher than that of the DWBC to silica distinctly lower is abrupt, across stations 91–93 suggesting division near station 92.

The I9S section, Fig. 3c shows that the southward rise of isotherms on the southern side of the AAB deep gyral flow steepens from station 93, suggesting an increasing westward flow at the sharp transition of θ-Si. On I8S southwestward from the AAB interior across the DWBC onto the Kerguelen Plateau, the same broad-scale rise of isotherms is seen, Fig. 3a. Thus the deep gyral flow in the AAB may include a recirculating interior pool of higher silica waters. The recent S4 section and Australian observations east of I9S should illuminate the eastern closure of this pool.

The interaction of the DWBC with the ACC

We now discuss the fate of these northern flowing waters east of Kerguelen as they encounter the Antarctic Circumpolar Current (ACC) entering the AAB from north of the Kerguelen Plateau. Park *et al.* (1993) extended a study of the ACC in the Crozet Basin to include the choke point between Kerguelen Plateau and Amsterdam Island. Their CTD and XBT data and satellite altimetry indicated the subtropical and subantarctic fronts (STF and SAF) compressed together between 44.5°S and 45.3°S, thus a narrow intervening subantarctic zone (SAZ); the (Polar Front (PF) was at 47.58°S. They calculated the bulk of the ACC transport ($100 \times 10^6 m^3 sec^{-1}$) concentrated in the STF–SAZ–SAF, with a $6 \times 10^6 m^3 sec^{-1}$ additional contribution in the PF. This transport feeds into the AAB along the southern flank of the Southeast Indian Ridge. Sections I8S and I9S cross this flow about 1600 km and 3400 km east of the Kerguelen–Amsterdam Passage. Along I8S the SAF lay between 42°S and 45°S with its southern edge directly over the Southeast Indian Ridge crest. I8S crossed the Polar Front (PF) twice at 51.5°S, 89°E and at 53°S, 87°E; both over 5° south of the mid-ocean ridge (the ambiguity was due to an eddy or meander embedded in the section). Along I9S the SAF lies between 46°S–49°S, north

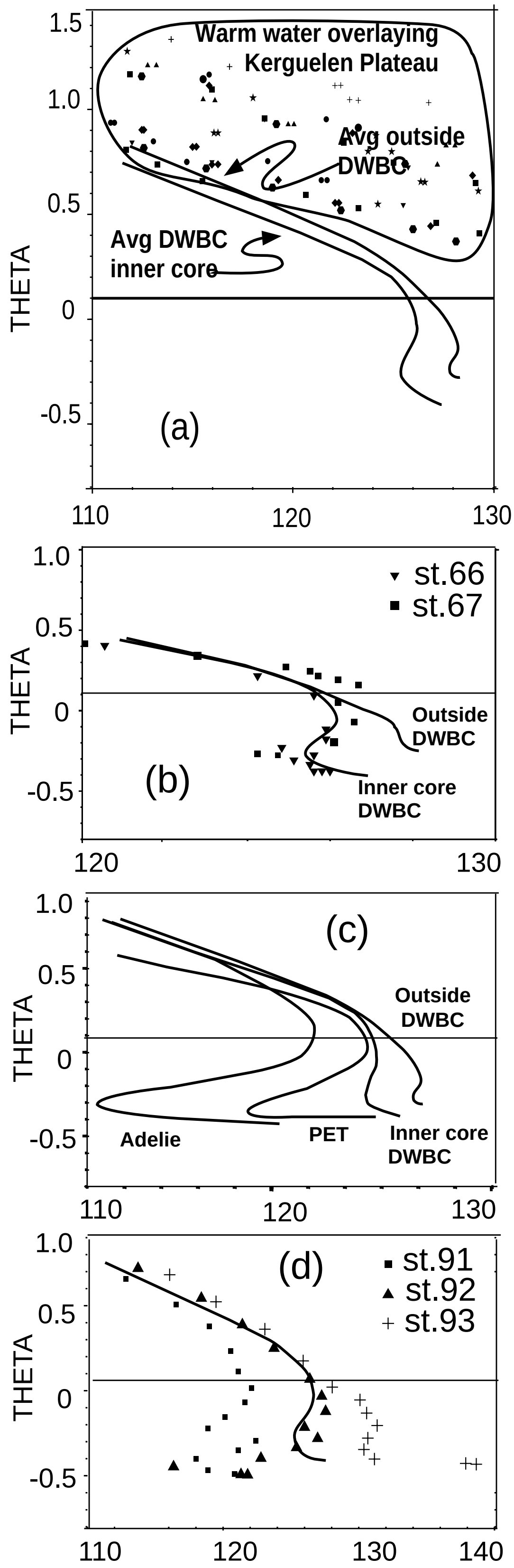

Figure 4. Theta-silica plots for WHP I8S and I9S section data through warmer core of DWBC and adjacent Kerguelen waters (a), colder core of DWBC (b), DWBC core and potential sources (c) and inner core of DWBC and Adelie Coastal Current (d).

of the Southeast Indian Ridge. The PF was at 51°S, much closer to the SAF and coinciding with the mid-ocean ridge crest. The bulk of the ACC transport thus has crossed the Southeast Indian Ridge, whose crest descends eastwards from above 3000 metres to below 2500 metres between the two sections.

The ACC brings deep water towards the Kerguelen-Amsterdam Passage at temperatures no colder than about 0.73°C, the coldest observation in the easternmost section by Park *et al*. (1993), near 3620 m, under the ACC axis. That section lies west of the sill of the passage, indicated in ETOPO5 digital bathymetry at 3140 m. In their section the coldest temperature at the sill depth is 0.87°C located at the base of the northern flank of the Kerguelen Plateau under the PF. We expect that the coldest deep water flowing eastward through this passage into the AAB falls in the range 0.7°C–0.9°C. In I8S (Fig. 3a), beneath the southern parts of the ACC (south of the Southeast Indian Ridge crest), deep water as cold as 0°C is associated with the deeper extension of the vertical shear signature of the ACC (north of station 50). The northward deep water transport of the DWBC evidently converges with and intrudes beneath the ACC as it flows into and along the northern AAB. In the process the DWBC must turn eastwards and descend some 1000–1500 m to get the waters between 0°C and 0.7°C on the slope of the Kerguelen Plateau down to their observed placement on the deep flank of the Southeast Indian Ridge. In I9S, Fig. 3c, along the southern flank of the Southeast Indian Ridge these same cold (<0.7°C) waters extend from 2400–4000 m, well above the Ridge crest to the north. The deep shear of the ACC, however, causes those isotherms to descend and intersect the Ridge south of the crest, except, marginally, 0.6°C and 0.7°C. Thus leakage of the DWBC waters across the Southeast Indian Ridge should occur mainly east of I9S, through the Discordance Zone, as anticipated by Mantyla and Reid (1983 and 1995). The intrusion of the DWBC waters beneath the ACC in the confluence region northeast of the Kerguelen Plateau sets the stage for this penetration of cold deep water across (under) the ACC being completed at the Discordance.

The flow of deep water from the Australian –Antarctic Basin to the South Australia Basin (SAB)

North of the Southeast Indian Ridge in the SAB, minimum temperatures are just above 0.5°C along I8S and just colder than that along I9S in the middle of the SAB. Examination of the I9S data show this bottom layer in the SAB is considerably warmer and lighter than the available pool of coldest water immediately south of the crest of the Southeast Indian Ridge. There are two extreme mixing alternatives for SAB bottom water evolution from the source waters from the south. One extreme is that the ridge dams up the cold dense waters below the (unknown) Discordance sill depth, so only waters warmer than sill depth flow over into the SAB. Perhaps that temperature is near 0.5°C, but in addition to not knowing the Discordance Zone sill structure, the local height of isotherms above the sills will reflect the exact placement of the ACC over the region, since the isotherms steeply slope across the ACC. The other extreme is that the coldest densest available waters leave the AAB through the Discordance Zone and strongly warm and lighten by entrainment of the overlying ACC waters. We favour something closer to the first scheme, because if there were substantial entrainment or mixing with the overlying warmer deep waters, it is hard to see how the SAB bottom water could end up only slightly altered from conditions on its isopycnals south of the ACC. The SAB bottom water does exhibit higher temperature and salinity and lower silica and oxygen than waters on the associated density surfaces south of the Ridge, but these anomalies are rather small.

A Deep Northern Boundary Current along the southern Australian continental slope

North of the ACC, the I9S data indicate a weak deep shear across SAB, with most of the “action” in a 200 km wide boundary against the continental slope of Australia. At thermocline levels a broader northward rise of isotherms indicates the Flinders Current (Bye, 1972) flowing westward and providing a partial recirculation gyre in the SAZ. The deeper shear signature is the same sign to around 3500 db, and isotherms reverse slope sharply below 3500 db. This shear reversal is not particularly strong, however, for the vertical density gradient is not large. If one imagines the Flinders Current to have a shallow reference level, then below that level the flow reverses to eastwards, reaches a maximum eastward speed near 3500 db (θ = 1.3°C), then declines below that core. The shear reversal allows the possibility that flow might reverse to westward near the bottom. One requires westward flow in the cold bottom layer between the Australian coast and about 45°S, for the pool of water colder than 0.5°C must be making its way from the Discordance Zone southeastward of the section to

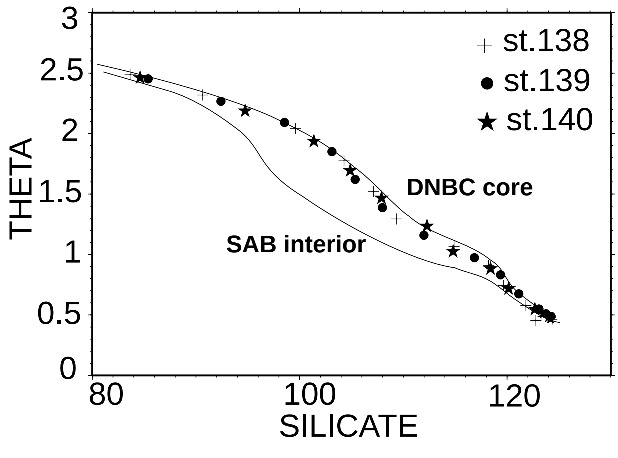

Figure 5. Theta-silica plots for WHP I9S section data in the South Australia Basin.

pass between the Broken Ridge and Naturaliste Plateau, where coldest bottom waters have warmed to about 0.54–0.55°C, Fig. 3b. Whether this flow occurs at the bottom of this DNBC system or to its south, or both, will involve sorting out subtleties of the bottom water characteristics and reference level issues. For now we note that the bottom water south of the DNBC is very slightly colder than that in the DNBC stations, with the transition occurring through stations 137–138, the same station pair defining the sharpest deep shear reversal, and for which there is a transition from slightly lower to higher silica below 0.7°C, Fig. 5. Our first guess is that the principal westward bottom water flow occurs in the offshore part of the DNBC.

The DNBC otherwise appears to be an eastward flow regime. In Fig. 5 the DNBC is seen to have a distinctly elevated silica for 0.7°C≤θ≤2.5°C, and we attribute this to origins in the southward flow near the Naturaliste Plateau described by Toole and Warren (1993) and Talley and Baringer (1995): this flow apparently turns the corner at the Plateau to flow eastwards through I9S. Defining the top of this eastward flow essentially defines a level of no motion for the DNBC above which the flow reverses to the westward flow of the Flinders Current. There is a pronounced oxygen minimum centred on θ = 2.5°C spanning the DNBC and extending southwards to station 132, and such waters are also found spanning the passage between Naturaliste Plateau and Broken Ridge, and it is tempting to assert eastward flow at this level in the DNBC across, transitioning to westward flow in the overlying Antarctic Intermediate Water. But since the gyral flow defined by the Flinders Current in the North and the SAF in the ACC to the south may penetrate to or into the oxygen minimum layer.

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OOPC Ocean Climate Time Series Workshop
Baltimore, 18-20 March 1997
Cosponsored by GOOS GCOS SCOR/JGOFS WCRP

The term time series here refers primarily to observations at fixed sites, but also includes repeat sections and observations from drifters. Such data have provided invaluable, sometimes unique, information for monitoring and detecting climate change and for understanding variability over a range of time scales in the physics, chemistry and biology of the ocean. In recent time logistical and cost factors have provided severe constraints on the maintenance and implementation of time series stations, in many cases leading to the cessation of data collection. However, this period has also been the introduction of innovative, more cost effective techniques for data collection and communication from moored/fixed platforms, perhaps making time series stations once more an effective observational method.

It is timely then to organise a review of the contribution to ocean science from time series, in particular those recently established under the JGOFS, TOGA and WOCE research programmes, and to assess

(i) the viability and feasibility of maintaining the existing stations,

(ii) the possibility of re-occupying sites for which long records exist and for which new technology might offer more cost-effective systems, and

(iii) identifying, on the basis of research results from programs like WOCE, TOGA and JGOFS where there are sound cases for establishing new sites.

The workshop will provide guidance to GOOS and GCOS, through the Ocean Observations Panel for Climate (OOPC), as they seek to identify sites that should be maintained routinely as a long-term contribution to climate monitoring. The results and recommendations from the workshop will also take into consideration the research interests of JGOFS and the nascent CLIVAR programme.

The workshop is planned to take place at Johns Hopkins University in Baltimore with local arrangements kindly handled by SCOR. A full 3-day meeting is planned with 20-25 participants. This should allow the diversified group to discuss and develop useful recommendations and prioritisation transcending boundaries between individual programmes and disciplines.

Organizing committee

Art Alexiou, IOC
John Field, JGOFS (ex officio)
Elizabeth Gross, SCOR
Ed Harrison
Peter M. Haugan (chairman)
Neville Smith, OOPC (ex officio)
Gerold Wefer
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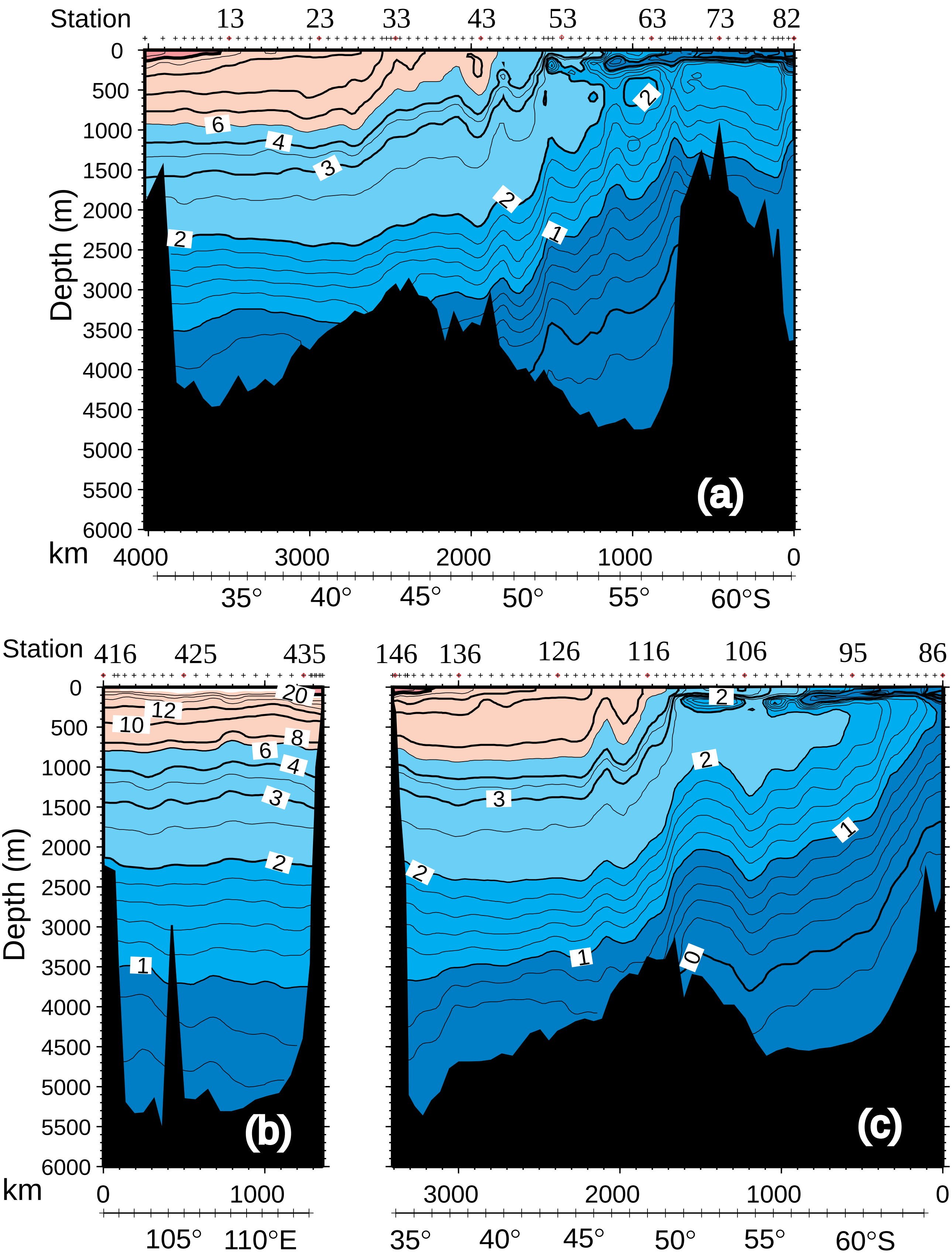

Hufford and McCartney, page 31, Figure 3. *Potential temperature cross sections: (a) WHP segment I8S; (b) a portion of WHP segment I8N5E; and (c) WHP segment I9S.*