On the potential temperature in the abyssal Pacific Ocean

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ABSTRACT

A new map of the potential temperature at the bottom of the Pacific Ocean has been prepared. It allows a more detailed description of the abyssal flow than has been possible before. In addition to the generally northward flow of the Pacific Bottom Water, some evidence is presented for the manner of modification of the Bottom Water, by vertical mixing and geothermal heating, into Pacific Deep Water, which must return southward above the Bottom Water layer. Near the Hawaiian Islands the two layers are separated vertically by a maximum in hydrostatic stability. Because they both have very weak vertical gradients of potential temperature, each contains an in situ temperature minimum. This structure creates a double in situ temperature minimum in that area.

1. Introduction

Surface water in the North Pacific Ocean approaches freezing temperature in the winter, but there the salinity is too low for overturn below a few hundred meters (Reid, 1973). The surface density in the North Pacific does not reach values greater than 1.0268 g/cm$^3$ at any time of the year (Reid, 1965), while the potential density near the bottom of the North Pacific is greater than 1.0278 g/cm$^3$. Thus the source of bottom water in the Pacific must be in the south, as has been recognized for nearly a hundred years (Prestwich, 1876). As the bottom water spreads northward into the Pacific basins, it becomes warmer through processes of mixing with warmer, shallower water and bottom heat flow. At abyssal depths in the Pacific, the water of lowest potential temperature in the column is densest and lies deepest. A chart of the bottom potential temperature should reveal pathways of the coolest (densest) water as it spreads into the Pacific basins. Caution must be exercised in using such charts, since the bottom depth varies and potential temperatures in the deep Pacific are higher at shallower levels. Nonetheless, low-temperature tongues should reflect penetration of bottom water into the Pacific because of the single source of cool bottom water.

Bottom temperature charts of the Pacific Ocean have been made in the past (such as those by Wüst, 1937; Panfilova, 1967; Olson, 1968; and Gordon and Gerard, 1970). Wüst (1937) did not consider data shallower than 4 km, yet passages between major basins are often shallower than 4 km. Wüst (1937) also showed temperatures
Figure 1. Simplified bathymetry of the Pacific after Menard (1964), with slight modifications from charts by Mannerickx et al. (1971) and Heezen et al. (1972). Areas less than 3 km deep are shaded; 4-km and 5-km isobaths and place names mentioned in text are indicated.

of less than $0.6^\circ C$ near the Sea of Okhotsk, leading Defant (1961) and Neumann and Pierson (1966) to assume that the Sea of Okhotsk was a source of bottom water in the North Pacific. The feature is not confirmed in the present set of data, or in the study by Wooster and Volkmann (1960). The temperature of less than $0.6^\circ C$ is from the Tuscarora in 1873 (Belknap, 1876) and appears to be faulty.

Panfilova (1967) used near-bottom in situ temperatures at depths between 1 km and the bottom. For comparisons of temperatures at different depths, potential temperature is preferred, and the present study uses potential temperature.

Olsen (1968) used bottom temperature at depths greater than 5 km only, limiting his investigation to just the deeper basins of the world oceans. The present study
Figure 2. Distribution of near-bottom potential temperature (°C) in the Pacific Ocean. Areas less than 3 km deep are shaded.

uses primarily data from deeper than 3 km, although somewhat shallower data are considered in the Southern Ocean.

Gordon and Gerard (1970) investigated the bottom potential temperature in the North Pacific, using the historical data and some recent heat-probe measurements, but did not discuss the South Pacific.

Within the last few years a greater number of accurate temperature measurements has become available to provide a more detailed picture of the entire Pacific. Although there are still some substantial areas lacking precise temperature measurements, the present study incorporates over 1300 selected stations reasonably well spaced over the entire Pacific, allowing a more detailed description than has been possible
in the past. A simplified bathymetric chart of the Pacific is shown in Fig. 1, and the bottom potential temperature distribution in Fig. 2.

The new bottom potential temperature chart illustrates the importance of bottom topography in shaping pathways of flow. Trench systems allow penetration of extreme water characteristics over great distances, particularly through the Japan-Kuril-Aleutian Trench system. With the addition of more recent data, Fig. 1 shows that isolated low temperatures in the North Pacific that appeared on the charts of Wüst (1937) and Gordon and Gerard (1970) are actually connected to the rest of the Pacific.

2. Pacific bottom potential-temperature distribution

The lowest potential temperatures in Fig. 2, less than \(-0.5^\circ \text{C}\), occur in the South Indian Basin at approximately \(60^\circ \text{S}\) between \(110^\circ \text{E}\) and the Macquarie Ridge. This cold water is predominantly from the Weddell Sea (Antarctic Bottom Water, AABW) and is probably somewhat modified by admixture of antarctic continental-shelf water (Gordon and Tchernia, 1972). The AABW is confined by ridges from spreading farther north.

The close spacing of the isotherms north of the \(-0.5^\circ \text{C}\) isotherm is caused by a combination of the shoaling of the bottom northward toward the Southeast Indian Rise and the northward deepening isotherms intersecting the rise. The water in the South Australian Basin is approximately \(1^\circ \text{C}\) warmer than that south of the rise, showing that the rise is an effective barrier to northward penetration of extreme AABW.

The Southeast Pacific Basin is somewhat warmer than the South Indian Basin, though still typically below \(0^\circ \text{C}\) in potential temperature. The water enters this basin by flow across the Macquarie Ridge, but is probably influenced by input from the Ross Sea (Lynn and Reid, 1968; Reid and Mantyla, 1971). The isotherms to the north are closely spaced, just as those between Australia and Antarctica, with the Pacific-Antarctic Ridge providing a barrier to northward spreading of bottom water.

From the Antarctic Circumpolar Current three tongues of low temperature extend northward into the Tasman Basin, the Southwest Pacific Basin, and the Southeast Pacific Basin. The Tasman Basin is closed at the northern end by a very shallow ridge and does not contribute bottom water to the other major basins of the Pacific. The northern edge of the Southeast Pacific Basin is blocked by the Chile Rise. Water from higher latitudes does extend across the Rise at shallower levels, and though it is somewhat warmer than deeper water to the west, it is extreme enough to be traced northward in the Peru-Chile Trench almost as far as the equator. Whatever influence this water contributes to the deep Pacific is confined to the eastern basins of the South Pacific.

The major flow of bottom water into the Pacific is clearly by way of the Southwest Pacific Basin, a cool tongue of potential temperature \(0.6^\circ \text{C}\) extending to about \(15^\circ \text{S}\)
in the Kermadec-Tonga Trench. The water that enters the Pacific is from the northern edge of the Pacific-Antarctic Ridge. The bottom water originally at 0.3°C extends slightly north but warms as it goes, the 0.4°C and 0.5°C isotherms clearly projecting into the Southwest Pacific Basin.

The bottom water entering the Pacific was shown by Reid and Lynn (1971) to be highly modified lower North Atlantic Deep Water and Antarctic Bottom Water, plus a third component, probably Antarctic Intermediate Water (Craig and Gordon, 1965). Though recognized as remnants from other sources, the bottom water entering the Pacific will be referred to as Pacific Bottom Water (PBW) in the following (Sverdrup et al., 1942, referred to it as Pacific Deep Water of diluted Atlantic and Indian origin).

From the model of abyssal circulation by Stommel (1958), the most intense boundary current would be expected to be along the western boundary in the southern hemisphere. This has been confirmed in the South Pacific from the Scorpio data (Reid et al., 1968), though the deeper bathymetry in the western side of the Southwest Pacific Basin is also a contributing factor. Pacific Bottom Water is restricted from flowing northward to the west of Samoa by the Robbie Ridge (Reid and Lonsdale, 1974). The deepest passage from the Southwest Pacific Basin to the Central Pacific Basin is the Tokelau Passage, where high near-bottom velocities have been measured (Reid, 1969).

North of the Tokelau Passage, the PBW appears to split into two branches, as indicated by the 0.8°C isotherm. Farther north, the 0.9°C and 1.0°C isotherms show penetration of the PBW more to the north in the western Pacific than in the eastern Pacific. The deepest passages and basins are in the northwest Pacific, causing the larger portion of PBW to take this route.

Edmond et al. (1971) have described the eastward penetration south of the Hawaiian Islands through the Horizon Passage. Recent bathymetry charts of the North Pacific (Chase et al., 1971) show the Clarion Passage to be a deeper and wider passage, so major flow should take place there also. The bottom potential temperature is similar in the two passages, 0.86°C in the Clarion and 0.87°C in the Horizon passage, confirming that both passages are important for bottom water penetration to the east. Eastward penetration of PBW has been detected as far as 20°N 126°W (Mantyla, 1969). Along the equator, PBW extends as far east as the East Pacific Rise, apparently channeled by the deeper troughs between fracture zones in the eastern Pacific (Wong, 1972). Johnson (1972) has reported easterly bottom currents of approximately 5 cm/sec near the Clipperton Fracture Zone (8°N 134°W). At shallower levels, deep water appears to cross the East Pacific Rise at approximately 5°S 125°W, as shown by the 1.4°C and 1.5°C isotherms. The Guatemala Basin and Middle America Trench seem to receive water from two different paths: the Sequieros Fracture Zone at 7°N 102°W and between the East Pacific Rise and the Cocos Ridge. Local in situ double temperature minima appear in this basin (Fig. 3), reflecting two sources through sills of different depth. Double temperature minima also appear near Hawaii,
discussed in a later section. The Panama Basin appears to fill from a single gap between the Carnegie Ridge and Ecuador (Laird, 1971).

The 1.05°C isotherm in Fig. 2 suggests that the northward extent of the eastern branch of PBW reaches as far as 30°N. Both the northward and eastward extents of this branch appear to be greater than suggested by Edmond et al. (1971).

Beyond the extension of the western branch through the passage to the east of the Marshall Islands, the PBW again appears to be divided by the bottom topography, this time into three paths (as indicated by the 1.0°C isotherm). One branch extends westward into the Philippine Basin. Another branch goes northwest into the Japan Trench and can be traced through the Kuril Trench into the Aleutian Trench. The third branch goes into a depression between the Shatsky Rise and the Emperor Seamounts, where further penetration northward is hindered by slightly shallower topography.

Of the numerous passages along the Emperor Seamounts and the Hawaiian Ridge, the coldest bottom water appears to have best access to the passages northwest of Midway Island. These passages are of similar depth to those at Horizon and Clarion passages and allow flow of bottom water eastward into the Northeast Pacific Basin, where it converges with flow extending northward to the east of Hawaii. PBW also enters the Northeast Pacific Basin by way of the Aleutian Trench, though that source seems to be of limited importance. Similar paths of flow in this region were inferred by Reed (1969).

The Northeast Pacific Basin appears to be the terminus of the main path of PBW flow into the North Pacific (Wooster and Volkmann, 1960). The bottom potential temperature is greater than 1.1°C there, and bottom charts of dissolved oxygen and silicate (not shown) indicate that the lowest bottom oxygen and highest bottom silicate occur in this region. Thus the null point in PBW circulation occurs in the northeast Pacific.

3. Double in situ temperature minima near Hawaii

To the east of Hawaii is a region where double in situ temperature minima occur. The feature was first noticed in data from station 26 on the Tethys expedition in 1959 (Scripps Institution of Oceanography, 1969). The station was re-occupied by two other expeditions, Ursa Major and Zetes (Scripps Institution of Oceanography, 1967 and 1970), and both seemed to confirm the feature, although the extrema are close to the precision of deep-sea reversing thermometers. Later use of continuous temperature probes (Chung et al., 1969; Craig et al., 1973) have also shown the
feature. Plots of in situ temperature along two postulated paths of flow around Hawaii (Figs. 4, 5, and 6a) help to elucidate the feature. Starting with a station at the equator north of the Tokelau Passage, the profiles go in a clockwise direction through the Wake Island Passage, a passage near Midway Island, around Hawaii, through the Clarion Passage, and ending at the equator station again. At all stations south of the Midway Island and Clarion passages, the in situ temperature minimum lies at a depth of 4.5 to 5 km, while in the Northeast Pacific Basin it is at a depth of 3.7 to 3.9 km, with the two minima superimposed at the station east of Hawaii. A shallow temperature minimum could be produced by shallow sill depths into a basin, but the Midway and Clarion passages have similar sill depths. However, the effective sill depth for a particular passage could be somewhat shallower if the passage were constricted. Figure 6a indicates the width of the passages at a depth of 4 km, and the Midway Island Passage is narrower than the others.

Along the section, the isotherms at 3 to 4 km rise toward the Northeast Pacific
Figure 6. Vertical sections of properties along the paths shown in Fig. 4. Passage widths at 4 km are indicated for Wake Island, Midway Island and Clarion passages. (a) In situ temperature (°C), (b) Potential temperature (°C). Vertical exaggeration 2000:1.

Basin. Since there is no surface source of dense cool waters in the North Pacific, the cool water at 3 to 4 km can only come from below. If the lower temperature were due only to adiabatic cooling with rising bottom water, the upper temperature minimum would be lower in value than the deeper minimum. However, almost all of the temperature minima north of 30°N in the Pacific are at nearly the same temperature, 1.48°C ± 0.02, although the two minima are approximately 1 km different in depth. Thus, some mixing must occur with overlying warmer but less
saline water, the mixing rate having the same order effect as adiabatic cooling of the rising bottom water.

4. Origin of North Pacific Deep Water

The bottom water in the Northeast Pacific Basin is warmer (potential temperature greater than 1.1°C, Figs. 2 and 6b) than the rest of the deep, open Pacific. (The
eastern Pacific basins are quite separate, at abyssal depths, and are filled with even warmer water from shallower levels over ridges.) Although bottom heat flow might be expected to have similar effects upon the bottom water throughout the Pacific, in the northeast Pacific the PBW has reached a cul-de-sac and may remain longer in that region, resulting in a somewhat greater effect from heat flow than in other regions. Knauss (1962) has estimated that mixing with overlying waters is at least twice as important as bottom heat flow in the Pacific, but greater heat
flow in the northeast Pacific could account for the low vertical stability seen there (Fig. 6d) and induce greater vertical mixing.

It has been suggested that there must be a deep compensating southward return flow between the Antarctic Intermediate Water and the PBW (Wüst, 1929; Deacon, 1937). It appears that the origin of this return flow is the North Pacific (Reid, 1973). The water in the Northeast Pacific Basin below 3.5 km has low stability and very low vertical gradients in potential temperature, salinity, oxygen, and silicate (Figs. 6b–f). The potential temperature and silicate are high, while the salinity, stability, oxygen, and density are lower than in the bottom water in the South Pacific. Some of these characteristics can be seen in the north-south sections of Reid (1965), Reid and Lynn (1971), and Horibe (1970).

The North Pacific Deep Water (NPDW) seems to be simply PBW that has become modified by bottom heat flow and mixing with overlying water during the course of flow to the North Pacific, becoming less dense, lower in oxygen, and higher in nutrients. The return flow of NPDW is recognized in Fig. 5 by the inflections in the temperature curves south of 10°N at slightly less than 4 km, which is the same depth as the shallow temperature minimum to the north. The double temperature minimum near Hawaii is also a result of the NPDW overriding PBW near the origin of NPDW. The low stability of the water in the North Pacific is seen as a stability minimum between 3 and 4 km in the stations south of 10°N. Stability here is calculated from the expression of Hesselberg and Sverdrup (1914). Although the stability extrema are close to the precision of the stability calculation, many stations in the Pacific show the feature, and the extrema are believed to be real. The interface between NPDW and PBW is characterized by a stability maximum. A similar stability maximum also separates the deep and bottom water in the Atlantic and Indian oceans (Schubert, 1935; Reid and Lynn, 1971). The transition zone between the NPDW and PBW is clearly illustrated by the strong gradients in all characteristics shown in vertical distribution by Craig et al. (1972, Fig. 1). Reid and Lonsdale (1974) have used the deep stability maximum as a reference level in geostrophic current calculations in the region around the Tokelau Passage. The calculated NPDW flow was southward, in agreement with the water characteristics inferred to have originated in the North Pacific. It is not yet clear where the NPDW flows southward across the equator.

Because of the subtle variations in properties in the abyssal Pacific, Montgomery (1958) has referred to the deep and bottom water of the Pacific as “Common Water”. Knauss (1962) and Gordon (1970) believed that flow into the Pacific is northward below 2500 m. It has become evident that although the water below the Intermediate Waters is primarily from the south, northward flow occurs only below the deep stability maximum (typically about 4 km deep in most of the Pacific and deepest in the north, and somewhat shallower in the western boundary current). Above the deep stability maximum is a zone of low vertical gradients in all properties, derived from modified PBW in the northeast Pacific. The return flow is indicated
best by relatively low dissolved oxygen in the NPDW (Deacon, 1937) as seen in the north-south sections of Horibe (1970) and Reid (1965) and by relative high silicate as seen in the north-south sections of Horibe (1970) and the GEOSECS Pacific data.

5. Data sources
A total of 1,389 stations from 143 expeditions and eight countries (Australia, Canada, Denmark, Japan, Sweden, United Kingdom, U.S.A., and U.S.S.R.) were selected from the available historical and recent unpublished expedition data reports. Greater emphasis was placed on recent expeditions because they generally reached closer to the bottom and had closer depth spacing than the older expeditions.

Station selection was also based upon geographical spacing. Where more than one station was occupied within two degrees of latitude or longitude, preference was given to stations that had salinometer, oxygen, nutrient data and better depth spacing. Many historical stations have 500 to 1000 m depth spacing in the deep Pacific; 150 to 300 m spacing is preferred for distinguishing the subtle variations in the deep and bottom waters of the Pacific Ocean.

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REFERENCES


Prestwich, Joseph. 1876. Tables of temperatures of the sea at different depths beneath the surface, reduced and collated from the various observations made between the years 1749 and 1868, discussed. Phil. Trans., 165, Part II(21): 587–674, pl. 65–68.


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