EXERCISE 10

WATER MASSES AND TEMPERATURE–SALINITY DIAGRAMS

A **water mass** is a large volume of water that can be identified as having a common origin or source area. Water masses are formed by an interaction of water with the atmosphere or by the mixing of two or more bodies of water. Once formed they sink to a depth determined by their *density* relative to the waters above and below them in the vertical column. The important determinants of the density are *temperature* and *salinity*.

IDENTIFICATION OF WATER MASSES

Because water masses mix with the surrounding waters only very slowly, they tend to retain their original temperature and salinity. Thus the distinctive temperatures and salinities (and sometimes the oxygen content) of these masses make it possible to identify them. The identification is important because it gives us information on their place of origin, deep circulation, and the rates at which waters of different densities mix.

Deep circulation — the motion of water at depth — is called *thermohaline* (temperature - salinity, hence density) *circulation* and is almost completely separate from that of the surface currents. Whereas surface circulation is largely in an east - west direction and moves warm water toward the poles, deep and bottom currents transport water in a north - south direction, returning cooler water along the meridians toward the equator. The cold water eventually returns to the surface at some point to be reheated and returned to the poles by surface currents, or to mix with other waters and return to the depths. The velocity of thermohaline currents is very slow, about 1 centimeter per second, whereas surface currents are 10 or 20 times faster. Using out concept of residence time — the average time that a given substance (deep water in this case) remains in the ocean before being recycled (see Exercise 9) — about 500 - 1000 years would be required to replace all the deep water in the Atlantic Ocean.

The identification of large water masses in the oceans is made possible by careful collection of oceanographic data. The most useful data for this purpose

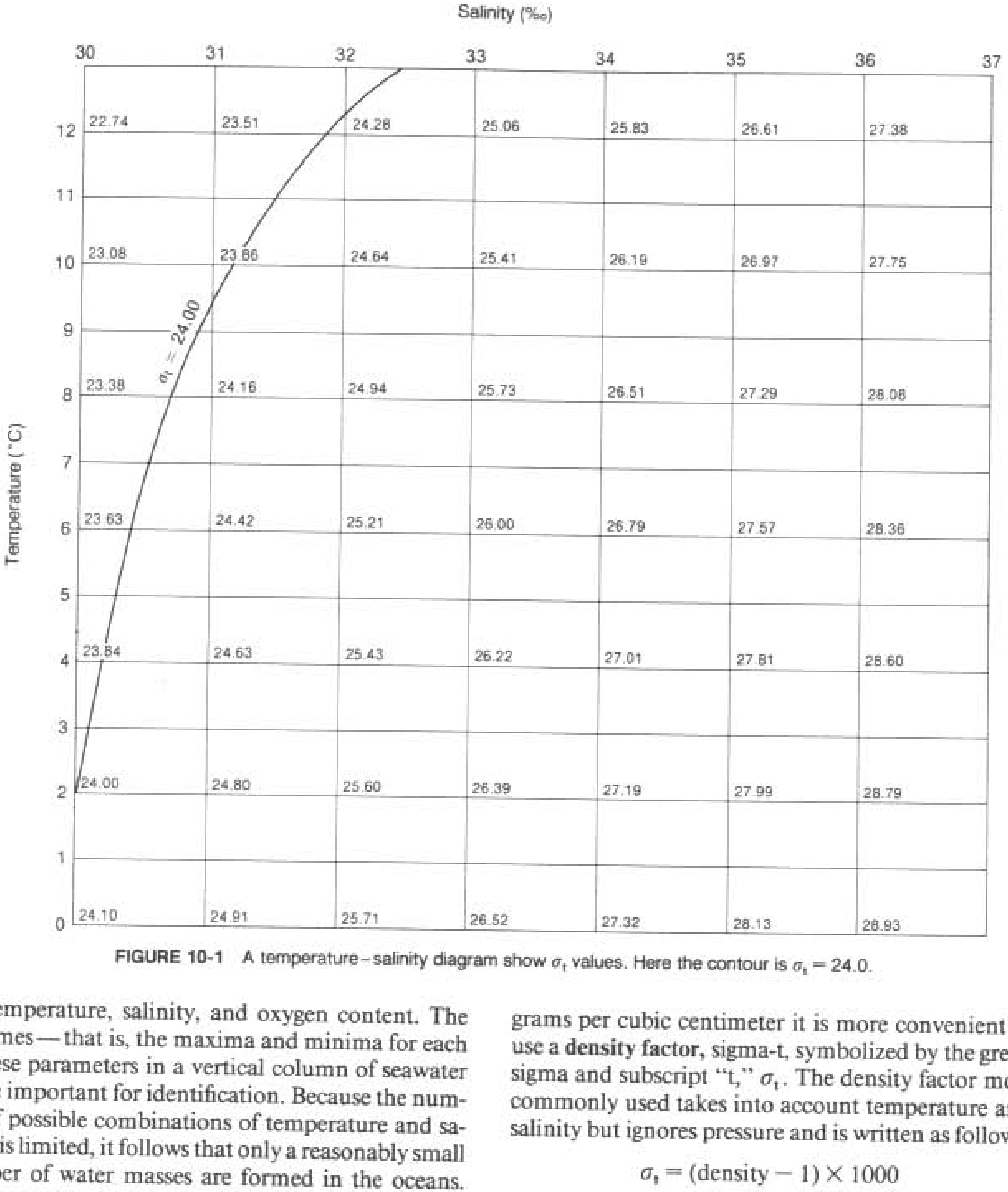


FIGURE 10-1 A temperature–salinity diagram show σ_t values. Here the contour is $\sigma_t = 24.0$.

are temperature, salinity, and oxygen content. The extremes—that is, the maxima and minima for each of these parameters in a vertical column of seawater—are important for identification. Because the number of possible combinations of temperature and salinity is limited, it follows that only a reasonably small number of water masses are formed in the oceans. However, the density alone of a water mass is not sufficient for its identification because various combinations of temperature and salinity can produce the same density.

THE DETERMINANTS OF DENSITY, AND THE DENSITY FACTOR

Temperature, salinity, and pressure are the determinants of density, which is measured in grams per cubic centimeter. Inasmuch as the density of seawater is always greater than 1.0 gram per cubic centimeter (the density of fresh water), and never as great as 1.1 grams per cubic centimeter it is more convenient to use a **density factor,** sigma-t, symbolized by the greek sigma and subscript "t," σ_t. The density factor most commonly used takes into account temperature and salinity but ignores pressure and is written as follows:

$$\sigma_t = (\text{density} - 1) \times 1000$$

Thus a seawater sample with a density of 1.02594 would have a $\sigma_t = 25.94$. Note that the mathematical manipulation involved in changing density to σ_t is simply dropping the 1 and moving the decimal point three places to the right.

TEMPERATURE–SALINITY DIAGRAMS

If we plot the density factors for a series of combinations of temperature and salinity on a **temperature salinity** (T–S) **diagram,** we see that contours of equal density, **isopycnals,** are curved lines (Figure 10-1). For example, water with a salinity of 32.00 parts per

TABLE 10-1
Density factor, σ_t values for various temperatures and salinities

Temperature (°C)	Salinity (‰)						
	30	31	32	33	34	35	36
0	24.10	24.91	25.71	26.52	27.32	28.13	28.93
2	24.00	24.80	25.60	26.39	27.19	27.99	28.79
4	23.84	24.63	25.43	26.22	27.01	27.81	28.60
6	23.63	24.42	25.21	26.00	26.79	27.57	28.36
8	23.38	24.16	24.94	25.73	26.51	27.29	28.08
10	23.08	23.86	24.64	25.41	26.19	26.97	27.75
12	22.74	23.51	24.28	25.06	25.83	26.61	27.38

thousand (‰) at a temperature of 10°C has a σ_t of 24.64 density = 1.02464). This value has been plotted in the *T–S* diagram in Figure 10-1 where the 10°C and 32‰ lines intersect. Note the isopycnal. Every point on this line has a σ_t of 24.00; for example, this line crosses the 12°C temperature line at a salinity of about 31.85‰. Thus a water type with a temperature of 12°C and a salinity of 31.85‰ has a σ_t value of 24.00 (density = 1.0240 grams per cubic centimeter). Table 10-1 gives σ_t values for the range of temperature and salinity conditions commonly found on the open ocean. Note that the highest density, 1.02893 grams per cubic centimeter, is yielded by the water type with the highest salinity, 36‰, and lowest temperature, 0°C.

From Figure 10-2, we can see that the mixing of two **water types** of the same density, but of different temperatures and salinities, will produce a water mass that is denser than the two that originally mixed. This mixing process is known as **caballing.** In the figure, water types A and B, which have the same density, mix to form water mass C. When mixed in equal quantities $T_C = (T_A + T_B)/2$, and $S_C = (S_A + S_B)/2$, but σ_{tC} is greater than $(\sigma_{tA} + \sigma_{tB})/2$, where T denotes the temperature, S the salinity, and σ_t the density factor. In general, the temperature and salinities that result from mixtures of water types can be computed by simple averaging, whereas density cannot. Caballing produces intermediate water masses (500–1500 meters), deep-water masses (1500–4000 meters), and bottom-water masses in the oceans. Figure 10-3 shows these water masses in the South Atlantic off

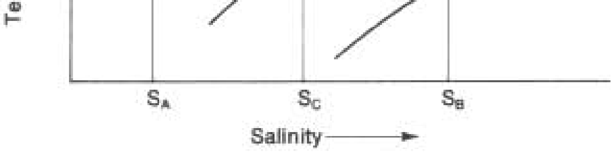


FIGURE 10-2 A temperature–salinity diagram showing the simple mixing of two water types, A and B, to form water mass C. Note that the density of C is greater than that of either of its end members A or B. The density increases from σ_{t_1} to σ_{t_4}.

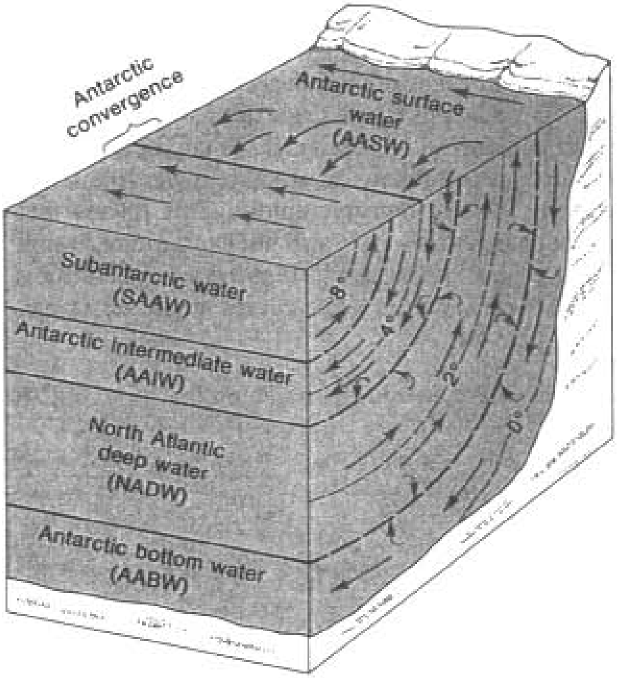


FIGURE 10-3 Complex thermohaline currents in the South Atlantic Ocean off Antarctica. Water cooled by sea and land ice of Antarctica sinks and flows along the bottom (AABW). It is replaced by an upward flow of warmer salty water (NADW), which mixes with surface water (AASW). Generalized isotherms show temperatures characteristic of the water masses. [After V. G. Kort, "The Antarctic Ocean." Copyright © 1962 by Scientific American, Inc. All rights reserved.]

TABLE 10-2
Subsurface-water masses in the North Atlantic Ocean

Water mass	Source	Identifying characteristic
Antarctic bottom water (AABW)	Weddell Sea	Bottom temperature minimum
North Atlantic deep water (NADW)	Area near Greenland	Intermediate salinity maximum, may show intermediate temperature maximum, low oxygen content in South Atlantic
Surface-water masses	Regional	Variable, generally warm
Mediterranean intermediate water (MIW)	Mediterranean Sea off Turkey	High salinity and temperature tongue at intermediate depths

Antarctica. Surface-water masses and types are generally formed by direct interaction and exchange between sea and air. The different water masses found in the North Atlantic Ocean are listed in Table 10-2.

When you plot the $T-S$ values for a real water station (as in Question 4 in the report form) you will note that they are in a stable position relative to each other because their densities increase as we go deeper in the column. The relative degee of stability is shown on a $T-S$ diagram by the angle the $T-S$ curves make with the contours of density. If the curves cut across the lines of equal density at large angles, the water column changes density rapidly. This means that minor changes in density will not cause water to sink or rise a great distance, and that the water column is therefore very stable. If the curves are at very small angles to the density contours, then the water changes density only slightly with increasing depth, so that minor changes in temperature and salinity (density) will cause water to move to different depths rapidly.

Also, a $T-S$ diagram in a well-known area of the oceans can be used to correct or find data points that are in error. The incorrect data appear as isolated points on the diagrams outside of the areas in which the water conditions are usually found.

DEFINITIONS

Caballing. A mixing of two water masses of identical *in situ* densities but different temperatures and salinities. The resulting water mass then becomes denser than either of its components.

Density factor(σ_t). A convenient numerical value for manipulating density data: $\sigma_t = (\text{density} - 1) \times 1000$. If density is 1.02386 then σ_t is 23.86.

Isopycnal, or isopycnic line. A line of equal or constant density.

Temperature-salinity ($T-S$) diagrams. Diagrams on which the characteristics of large masses of water are identified by plotting salinity and temperature data. Salinity is plotted with increasing values toward the right, and temperature is plotted with decreasing values downward. Depth at which each sample has been taken is usually indicated along the curve.

Water mass. A large volume of seawater that can be recognized as having a common origin. Water masses may be formed by interaction between air and sea or by mixing of two or more water types. A water mass is characterized on a $T-S$ diagram by a group of values that may be plotted as a curve or a straight line.

Water type. A homogeneous mass of water having well-defined temperature and salinity characteristics. It appears as a single point on a $T-S$ diagram.

EXERCISE **10**

REPORT

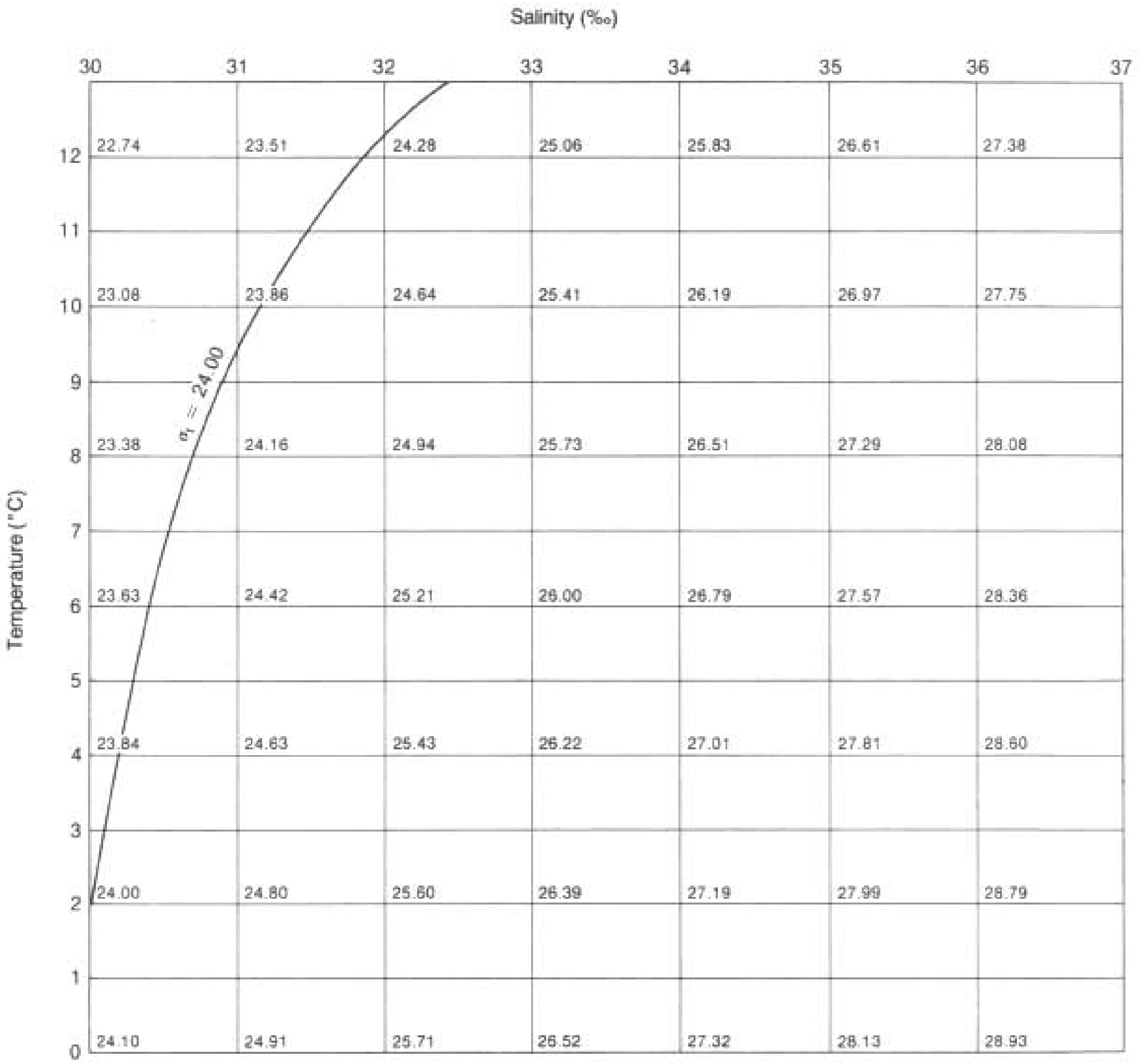
WATER MASSES AND TEMPERATURE—SALINITY DIAGRAMS

NAME ______

DATE ______

INSTRUCTOR ______

1. Below is a duplicate of Figure 10-1 in which the σ_t value for 24 has been plotted. Plot the values from $\sigma_t = 25$ to $\sigma_t = 28$ on the $T-S$ diagram.



2. On the 24.00 σ_t contour, plot a water type A where the contour crosses the 32‰ salinity line, and a water type B where it crosses the 6°C temperature line. Connecting these points with a straight line yields a mixing line for these two water types. Plot a point in the middle of this mixing line. Note that it falls below and to the right of the 24.00 σ_t contour and is therefore denser. This midpoint is the temperature and salinity of a 50–50 mixture of water types A and B. The line itself represents all possible mixtures of water types A and B and thus the water mass that would form from such a theoretical mixture.

(a) What is the range of *T* and *S* that defines your water mass?

(b) What is the density of the 50–50 mixture of water types A and B? (Hint: Interpolate between the 24.00 and 25.00 isopycnals.)

3. The following table gives the temperature and salinity data taken at one station. Plot the points on the *T*–*S* diagram that you contoured in Question 1, and connect them with straight lines.

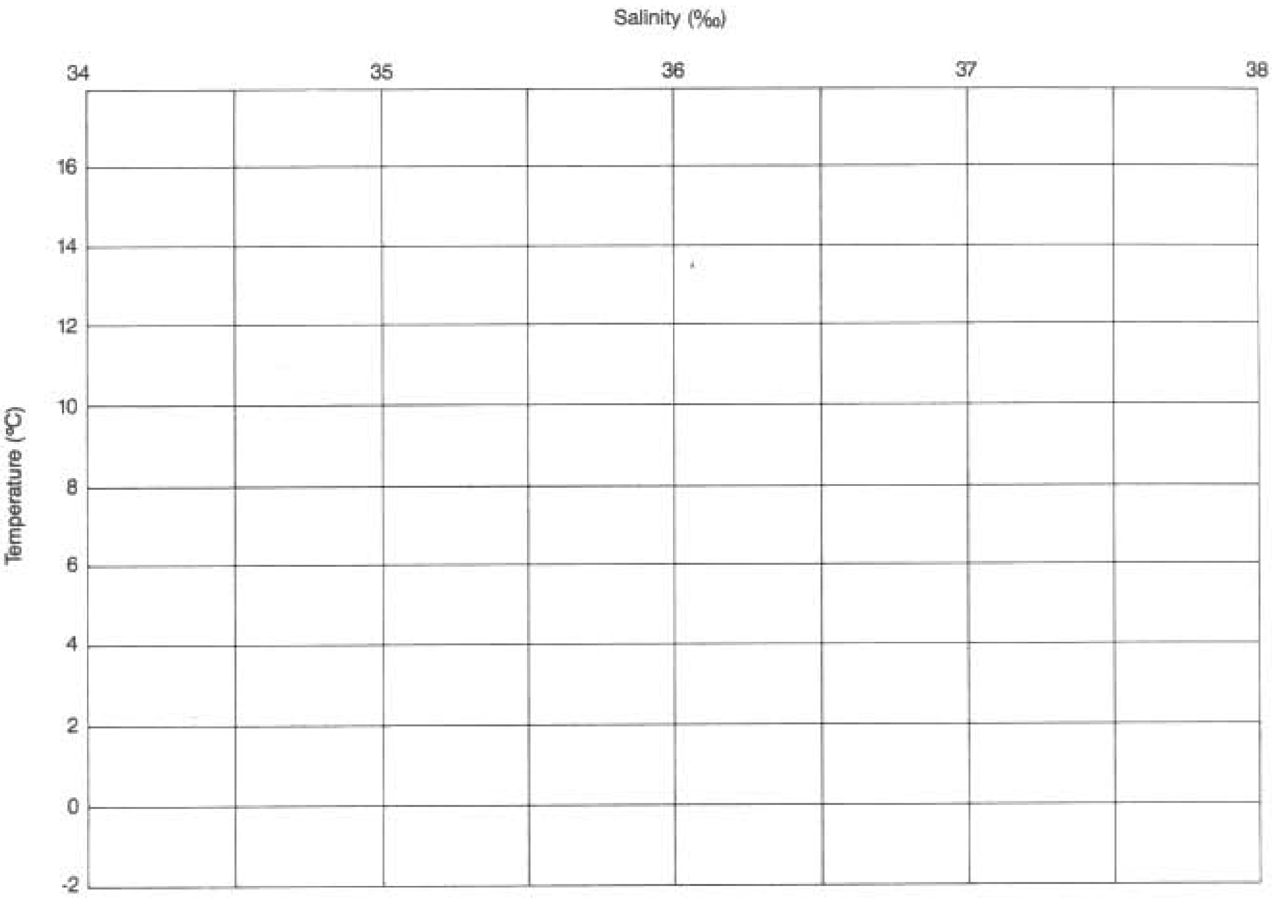
Depth (meters)	Temperature (°C)	Salinity (‰)
0	12	33.7
10	12	33.7
20	12	33.8
50	10	33.9
100	8	33.7
200	7	34.1
300	6	34.2
400	5	34.2

(a) What is the relative stability of the water column at this station; how deep is the mixed layer; and in what portion of the curve is the water most unstable (portion below the mixed layer)?

(b) In what portion of the curve is the water most stable?

4. The following are oceanographic data from a typical station in the North Atlantic at about La 20°N.

Depth (meters)	Temperature (°C)	Salinity (‰)
100	16.0	36.1
200	13.0	35.8
400	11.0	35.5
500	9.0	35.3
600	8.0	35.0
850	13.0	37.3
950	12.5	37.1
1200	11.0	36.7
1500	4.8	34.8
2000	4.0	35.0
2200	3.5	34.9
2500	2.0	34.8
3000	0.0	34.7
4000	−1.9	34.6
5000	−2.0	34.6



Plot the data on the blank *T–S* diagram above and draw a line connecting all points in order of depth. Using the diagnostic parameters provided in Table 10-2, name the major water masses represented in the diagram.

5. (a) It is estimated that the flow southward of North Atlantic deep water is 6×10^6 cubic meters per second. If the volume of the Atlantic Ocean is 3.24×10^{17} cubic meters, what would be the length of time required to circulate the entire Atlantic through the deep water?

(b) If the oceans are at least 3×10^9 years old, and we assume that the mixing rate has been constant, how many times has the ocean been "stirred" through the deep water?

(c) How long would you have to run a household blender spinning at 1000 revolutions per minute to equal the stirring of the oceans?

(d) Is the ocean a well-stirred solution?