FINESTRUCTURE, MICROSTRUCTURE, AND THIN LAYERS

By Thomas Osborn

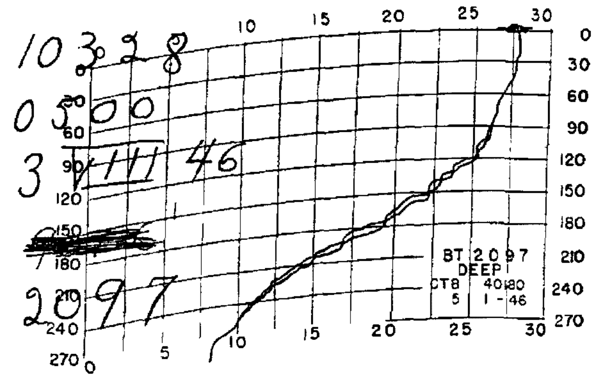

Fig. 1: Bathythermograph trace from Eckart (1948) showing temperature finestructure.

WE ARE ALL FAMILIAR with the irregular profiles from modern, high resolution conductivity-temperature-depth profilers (commonly called CTDs) freely falling vertical profilers, and towed thermistor chains (Figs. 1 and 2). In fact sufficient resolution was available back in the 1930s with the advent of the Bathythermograph (BT) (Eckart, 1948) and even earlier through the use of the thermocouple (Schmidt, 1914; and Hacker, 1933). Figures 3 and 4 show thin layers of biological material. Fish and copepods which swim can easily form layers, but what about some of the particles which are very small, neutrally buoyant, and only swim slowly, if at all. Are their profiles related to the temperature, density, or their gradients? The easily measured profiles of temperature, salinity, density etc., carry a signature of the relevant physical processes. How much do they tell us about the formation of the biological and chemical layers?

Microstructure refers to the signatures of oceanic turbulence at scales where moleulcar viscosity and diffusion are important. Quantitative measurements at these scales (millimeters to centimeters) provide estimates of the cross-isopycnal diffusion rates. Finestructure is the label for larger features where the stratification limits the motion to the horizontal plane. Signatures of this stirring motion have horizontal scales substantially greater than their vertical scales. Eckart (1948) created the paradigm of stirring and mixing, which shows the significance of the predominantly horizontal flow field, and the boundary conditions, in producing these irregular vertical distributions and layers.

Thin layers are superficially like the physical finestructure features in thickness and extent. This similarity is a result of the density stratification which forces most of the motion to be horizontal and makes sharp vertical gradients out of weak horizontal gradients. In fact, it is useful to consider thin layers as the biochemical equivalent of the finestructure in temperature, salinity, or density, with the caveat that the biological and chemical layers are forced by biochemical processes as well as physical processes. The biochemical processes interact and couple with the physical processes. However, while the coupling of processes may bind the biochemical layers to temperature, salinity, or density layers, it is the vertical shear of the horizontal currents in conjunction with the horizontal gradients that have a major role in forming both thin layers and finestructure. Since the horizontal variations of biological, chemical, and physical parameters can differ significantly, there is no *a*

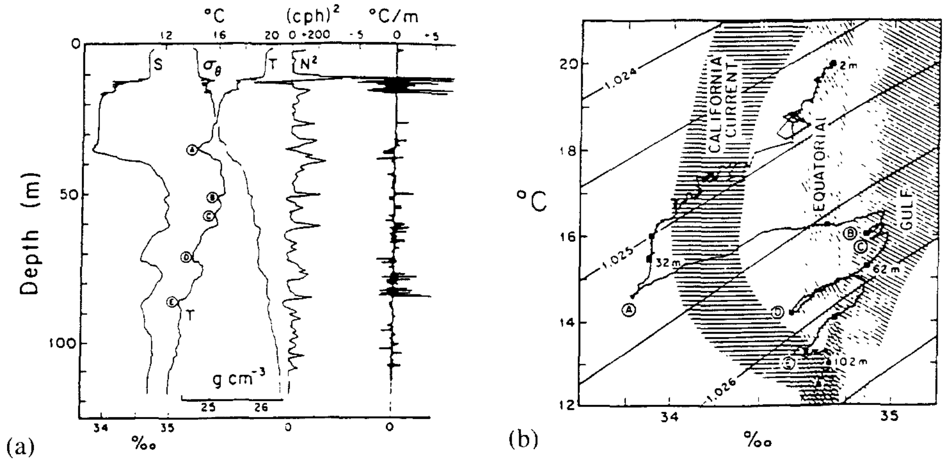

*Fig. 2: (**a**) Temperature, salinity, and potential density averaged over 0.03 m off Cabo San Lucas showing a multitude of intrusions and finestructure features (modified figure from Gregg 1975). N^2 is averaged over ~0.8 m to show the finestructure in the density. The temperature gradient has not been smoothed, showing how the variance is at the microstructure scales and the finestructure is not visible without averaging. (**b**) T-S diagram showing the different water masses in the region that contribute to the vertical profile.*

Thomas Osborn, Department of Earth and Planetary Sciences, The Johns Hopkins University, Baltimore, MD 21218-2681, USA.

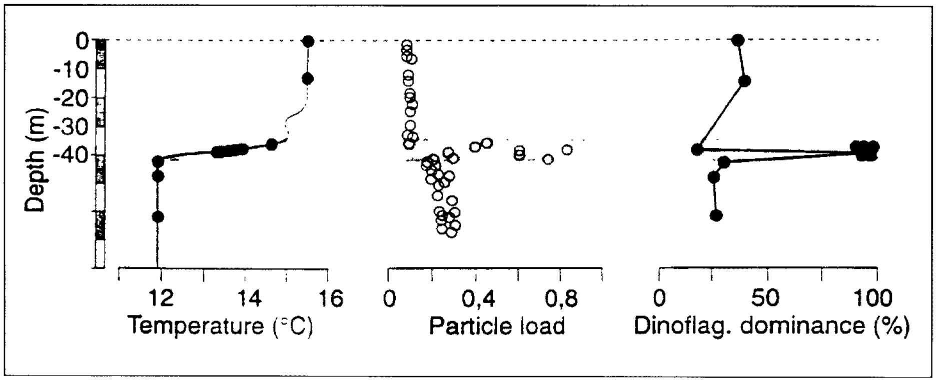

Fig. 3: Vertical profiles of La Rochelle, France, with an in situ particle size profiler after Gentien et al. (1995) showing temperature, particle load, and percentage of dinoflagellates (% total phytoplankton). The closed and open circles are the locations of water samples.

priori reason for thin layers and fine structure features to be firmly locked together. Crucial, first order, measurements include the vertical profile of the horizontal velocity with resolution at the vertical scale of the thin layers and finestructure in conjunction with the variation in horizontal and vertical distributions of the biological, chemical, and physical fields.

Carl Eckart: Stirring and Mixing

In his early and very insightful paper, Eckart related the finestructure in temperature profiles collected with a BT, to the physical processes of stirring and mixing. Stirring of the fluid is accomplished by the spatial variations of the velocity and has two effects (Fig. 5). First, it increases the interfacial area between water parcels with different characteristics, and, second, it increases the property gradients across those interfaces. Both of these effects increase the rate of transport by molecular diffusion. When molecular diffusion smoothes out all the spatial variations, the fluid becomes uniform, i.e., well mixed. Mixing is molecular diffusion removing the inhomogeneities created by the stirring.

Microstructure and Finestructure

Finestructure and microstructure are both signatures of the stirring. Microstructure is at the smallest scales, where molecular viscosity significantly affects the flow, and finestructure at larger scales where stratification is important (Gargett *et al.*, 1984).

Microstructure has scales that range from tens of centimeters downward, and the measurements are usually in terms of derivatives with respect to a spatial coordinate. The variance of the derivatives is concentrated at these scales and, for the case of velocity shear, determines the energy dissipation. Also, at these small scales the effect of stratification is limited, and the flow approaches isotropy. Both the temperature and velocity microstructure measurements produce estimates of the vertical eddy diffusivity (Osborn and Cox, 1972; Osborn, 1980), which compare favorably with direct measurements (Toole *et al.*, 1994; Ledwell *et al.*, 1993). This direct and quantitative application of the microstructure measurements has probably been a major reason why so much effort has been focused on microstructure for the last 25 years.

Finestructure as a term seems to apply to any wiggle or irregularity in a temperature, salinity, or density profile that can be seen by a CTD with vertical resolution of a meter. Fedorov (1978), in the introduction to the English edition of his book, uses the term "fine stratification," and the editor, J.S. Turner, identifies the generally accepted English equivalent as "finestructure." The signatures are interpreted as layers of the water extending much further horizontally than vertically. These features can be generated *in situ* by vertical mixing, they can be the result of intrusions from adjacent water masses, or they can be the ephemeral signatures of internal waves. In any case, they are the result of relative motion in the water. The T-S diagram (a plot of temperature against salinity) is a useful tool in separating intrusive finestructure from the effects of local mixing or internal waves Ochoa (1987).

Finestructure can be identified either by looking at the property directly or at the gradient profile (Grant *et al.*, 1961), if the gradient has been smoothed either by averaging the data or by using a sensor with limited frequency response. Full spectral resolution of the derivative reveals the microstructure scale variations that often obscure the mean trend. In Figure 2 the density profile and the N^2 profile was averaged over 0.8 m vertically and shows the finestructure, while the temperature gradient profile reveals the microstructure. Looking at finestructure with vertical gradient profiles involves an implicit averaging scale. The averaging scale is often not specified because it is "buried" in the details of the observing instrument and its role in how the data appears to the observer may not be appreciated.

Given that finestructure appears in both temperature and "averaged" gradient profiles, we must bear in mind that the two views of the same water are very different. First, an intrusion is usually thicker than its edges, at least the high gradient portion of its boundaries, so that while the temperature trace has one thick intrusion of order ≤10 m, the gradient profile sees two thinner boundaries, on the order of 1 m vertically. Again, Figure 2 has a nice example of a 20 m thick salinity minimum that is much less obvious from the profile of N^2. Second, although finestructure in the temperature and its gradient arise due to spatial variations in the temperature and velocity field, we will see that the way in which these phenomena cause temperature finestructure is not the same manner by which they cause finestructure in the temperature gradient. When we compare biological and chemical thin layers to the finestructure, we must be careful to recognize the different mechanisms for generating the finestructure.

Eckart's Analysis

Eckart started from the heat equation (neglecting solar heating) written in tensor notation (i.e., summation over repeated indices) but no Reynolds' decomposition.

$$\frac{D\vartheta}{Dt} = \kappa \frac{\partial^2 \vartheta}{\partial x_i \partial x_i} \quad \text{with} \quad \frac{D}{Dt} = \frac{\partial}{\partial t} + u_i \frac{\partial}{\partial x_i} \qquad (1)$$

where ϑ is the temperature, κ the molecular diffusivity for heat, i and j(=1, 2, or 3) are indices, x_i are the three coordinate axes (i = 1 is the x axis, i = 2 is the y