they disturbed the near-surface equilibrium temperature gradient.

The results of four experiments are under the set of conditions given in Table 1. The water temperature $\Theta$, and related Väisälä-Brunt period $T$, are given for various water depths. Phillips (5) indicates $T$ is the natural period of oscillation of a parcel of fluid which has been given a small vertical displacement from its equilibrium position in a stratified fluid. To a good approximation

$$T = \frac{2\pi}{60\left(\frac{g}{\rho_0}\frac{\partial\rho}{\partial z}\right)^{1/2}} \quad \text{min/cycle}$$

where $g$ is the acceleration of gravity, $\rho_0$ the reference density of the fluid, and $\partial\rho/\partial z$ the rate of change of density with depth. In experiments a and b, $\partial\rho/\partial z$ increased with depth and $T$ was everywhere real. In experiment c, $\partial\rho/\partial z$ and $T$ were both essentially constant. In experiment d, $\partial\rho/\partial z$ was slightly negative for $z<2$ cm, and thus $T$ was imaginary in this region. It was real for $z>2$ cm.

Smoothed results of the four exploratory experiments are shown in Fig. 1, where the time after the start of a submerged pulse of turbulent mixing is plotted against distance from the vertical centerline ℄ of the cell. Convergence $C$ near the surface is represented by the long-dash curves, divergence by the short-dash curves, and regions of zero convergence or divergence by the solid curves. (Curves to the left of ℄ are omitted because they would be mirror images of the ones shown.)

In experiments a to d the first convergence $C_1$, due to the simulated wake collapse, first reaches the surface at the ℄ where the pulse of submerged turbulent mixing started. The time for appearance of $C_1$ after the start of mixing was equal to $T(+13, -33$ percent) at the depth of initial disturbance $z=4.5$ cm. This result is consistent with my earlier results (3).

In experiments a to c the maximum value of convergence $C_m$ is located between 5 and 10 cm from ℄ on the $C_1$ curve. At these points $C_m$ changes the equilibrium temperature $\Delta\Theta$ by $+0.50°$, $+0.11°$, and $+0.06°$C, respectively (Fig. 1). The maximum convergence $C_m=\Delta\Theta/(\partial\Theta/\partial z)$ was approximately 0.05, 0.04, and 0.05 cm for the three cases. The thermistors used for measuring $\Delta\Theta$ were below the surface a distance $\Delta z=0.30$, 0.30, and 0.35 cm, respectively. Maximum vertical strain $S_v=C_m/\Delta z=0.17$, 0.13, and 0.14 for experiments a, b, and c. Average $S_v$ was about 0.15 which appears to be relatively insensitive to $T$ when the geometry was not changed.

Near the surface $S_v$ is obviously accompanied by a maximum horizontal surface strain $S_h$ which may be of about the same order of magnitude as $S_v$. The locations of $S_h$ for the experiments (Fig. 1) was between the long dashed curves and the solid curves, adjacent to the points of $C_m$. The slopes of the long dashed lines at the points of $C_m$ and $S_v$ gives a measure of the propagation velocity of these factors. The propagation of $C_m$, $S_v$ (and $S_h$) = 0.86, 0.55, and 0.26 cm/sec for experiments a, b, and c, respectively.

Experiment d (Fig. 1) is unique in that $T$ is imaginary for $z<2$ cm and real for $z>2$ cm. The center of the initial turbulent disturbance was at $z=4.5$ cm where $T=13.1$ sec/cycle. Thus, wake collapse was possible at mixer depth and produced convergence, divergence, and strain waves in the potentially unstable region near the surface. Maximum strain near the surface was found to be 0.16 which is essentially the same as for experiments a to c. For experiment d the propagation velocity of $C_m$, $S_v$, and $S_h$ was about 0.31 cm/sec for the conditions of the experiment. It was judged impractical to check the results of d (as well as a to c) against theory, that is not fully developed, in an experimental note.

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## Slumping Structures Caused by Organically Derived Gases in Sediments

Abstract. *The interstitial waters of many sediments are saturated with methane derived from the decay of included organic material. Further generation of methane or local pressure reduction results in sediment dilation and loss of sediment stability. The grains of sediment separated by gas behave in toto as an elastic fluid, and typical "slumping structures" result.*

Analysis and experiments have shown that clean sand, wet or dry, does not flow in response to stress. Rather, it falls along shear planes (1). The deformation of a mass of sand requires the expansion of that mass. The minimum expansion is required for the mass to fail along shear planes rather than by flowage. Flowage of a sand mass requires that any grain be free to move relative to the neighboring ones, a process requiring a large volumetric expansion that cannot be accomplished by stress alone. In order to fail under stress by flowage, sand grains must first be separated by some process other than stress.

Geologists have performed experiments in which sand was made to flow. These experiments, however, involved the use of interstitial plastic material, such as wax, so the flowage resulting under stress was actually the response of the wax to the stress field. The grains of sand were merely carried along within the wax. In the same way, sands containing adequate interstitial mud or clay can also fail by flowage if the sand grains are first separated so that individual grains do not become interlocked.

Despite the difficulty of accounting for the flowage of clean sands in response to stress, geologists have observed many examples of clean sands which have flowed, including spiral sand rolls, isolated sand rolls, sand crumpling, and sandstone dike injections. The fluid behavior of the sand masses is apparent in cases of sandstone dike injection, where fragile and sharp projections of shale on the containing walls of dikes often appear undisturbed, with their delicate points projecting into the invading sandstone mass. Many such fragments of shale are carried along as inclusions within the sand, their angular, fragile points

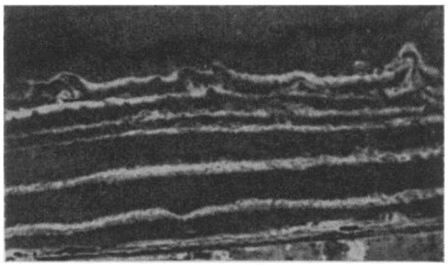

Fig. 1. Stratified sand containing gas in interstitial waters, illustrating the effects of gas on the mode of failure of the sediment. After gas leaves the solution in tilted beds (5° from horizontal), the mass fails by flowage as folds develop. (Note spiral roll at left.) Conversely, sand, either wet or dry, not containing gas, fails along shear planes and does not flow or fold.

still intact. The sand mass may also transport fragile pelecypods, which, in many cases, are preserved whole, sometimes with both valves still together. The grains of sand were entirely separated at the time of injection. The sandstone dikes, sand crumplings, spiral sand rolls, isolated spiral rolls, and other anomalous features commonly called slumping structures are usually found together. The cause of the fluidity of the sandstone dike materials may be the same as that of the fluidity required for the development of the flowage structures within the associated horizontal beds.

Most structures illustrating the fluidity of clastic materials are found in specific but seemingly diverse environments, including areas of petroleum accumulation and mud volcanoes, recent organic marine sediments, and strata contiguous to coal beds, glacial lake beds, and organic lake beds. These diverse environments have one characteristic in common: All of them are associated with large quantities of organic materials deposited under euxinic conditions.

As Sugden (*2*) has stated, "the vast majority of submarine slumps occur in sediments which have been recently deposited and particularly in sediments which must be supposed to have been rapidly deposited." The burial of large quantities of organic material under these euxinic conditions results in the formation of methane which saturates interstitial waters. The unconsolidated sediment is thereby capable of immediate elastic expansion, which results in pressure equalization throughout the volume of sediment. If a crack opens, the unconsolidated sediment expands immediately to fill it. The strength of the sediment is diminished to that of a fluid, since the grains of that sediment are separated by gas bubbles. In this way, clean sands can invade cracks within overlying shales at the instant the crack opens, without abrading the delicate shale projections observed later in the containing walls. When a horizontal layer of uncemented sand is saturated with gas, this fluid supports the total superincumbent load. Grains of sand are resting upon each other but are not bearing the unidirectional pressure of the overlying sediments. Any shift in weight of overburden results in an immediate rearrangement of the sand grains within the horizontal bed. The horizontal sand mass is capable of immediate expansion into continuously shifting low-pressure areas as the overlying sediments slump or slide, causing the typical slumping structures so often observed.

I demonstrated the flowage of stratified sand by means of a pressure tank, containing stratified sand and interstitial water saturated with $CO_2$. Reduction of pressure in the tank caused gas to leave solution, resulting in slumping structures (Fig. 1).

This same mechanism, that of dilatancy resulting from interstitial waters saturated with gas, affects the stability of marine sediments, forming structures which help to identify source beds of petroleum.

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## Equilibration of Atmospheric Carbon Dioxide with Sea Water: Possible Enzymatic Control of the Rate

Abstract. *Surface and subsurface ocean water differ in exchange characteristics with atmospheric carbon dioxide. The possibility of control by an enzyme like carbonic anhydrase has been experimentally explored.*

It has been discovered (*1*) that sea waters can differ markedly in their rates of equilibration with atmospheric $CO_2$. In surface waters the $C^{14}$ content resulting from nuclear weapons tests is on the average less than half that in tropospheric air, and it is only in a matter of years (*2, 3*) until full equilibrium is reached.

It has been well known for some time now (*4*) that in the analogous problem in mammals—namely, the

Table 1. Carbon dioxide exchange rates for sea water. Samples (200 liters) in polyethylene-lined barrels were capped, trucked to China Lake, and aerated at approximately 200 liter/hr for the indicated period, with or without addition of the enzyme carbonic anhydrase (CA). (No temperature corrections are applied).

| Sample No. | Date | Initial $\Delta C^{14}$* | Treatment: CA (mg) | Treatment: Time (days) | Final $\Delta C^{14}$* | Exchange time (days)† |
|---|---|---|---|---|---|---|
| *Surface waters (Santa Monica Beach at foot of Sunset Boulevard)* | | | | | | |
| 1 | 12/22/65 | 14.9 | None | 17 | 17.3 | 460 |
| 2 | 1/8/66 | 15.1 | None | 68 | 22.7 | 480 |
| 3 | 4/12/66 | 15.4 | 100 | 14 | 47 | 19 |
| 4 | 5/12/66 | 14.0 | 100 | 3 | 29.6 | 10 |
| *200-foot well at Pt. Mugu Naval Station* | | | | | | |
| 5 | 3/9/67 | —4.7 | | 7.6 | 23.9 | 14 |
| *200-foot submarine (U.S.S.* Baya*) sample (off Catalina Is.)* | | | | | | |
| 6 | 5/26/67<br>33°20'N 118°17'W | 6.7 | | 3.0 | 34.2 | 5 |
| *200-foot submarine (U.S.S.* Baya*) sample (off Catalina Is.)* | | | | | | |
| 7 | 7/25/68<br>31°40'N 120°20'W | 20.7 | | 2.7 | 37.1 | 5 |

* $\Delta C^{14}$ is the deviation from the National Bureau of Standards oxalic acid standard expressed in percent. † See Table 2.