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DEEP SCATTERING LAYER IN THE PACIFIC AND ANTARCTIC OCEANS

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INTRODUCTION

During Operation HIGHJUMP (U. S. Navy Antarctic Development Project, 1947), the writer frequently noted the presence of a layer of deep scatterers on the fathogram of the USS HENDERSON. This layer partially scatters the outgoing sound signal of the recording echo sounder during daylight hours so that a reflection is recorded which has the appearance of a false bottom at various depths between 150 and 450 fathoms.

Subsequent examination of a fathogram across the Pacific, as well as one from Hawaii to the Arctic, also revealed the frequent display of this phenomenon. As these records greatly increase present knowledge of the geographic distribution, and as other new information was observed regarding this phenomenon, the results of an examination of these fathograms is presented in this paper.

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PREVIOUS INVESTIGATIONS

Previous observations (Anon., 1942, 1943, 1946a, 1946b, 1946c) with sonar gear since 1942 by workers at the University of California Division of War Research and later at the U. S. Navy Electronics Laboratory, the Scripps Institution of Oceanography, and the University of California Marine Physical Laboratory, revealed that sound scatterers are not uniformly distributed in the ocean, but that they exhibit a

striking variation with depth. Frequently, at about 175 fathoms, an exceptionally well defined layer of scatterers was found that had at least ten times the scattering power of scatterers at shoaler depths.

It was noted that this Deep Scattering Layer¹ (D. S. L.) is principally a daytime phenomenon. In the morning, scatterers descended from near the surface to form the D. S. L. and, in the evening, they ascended toward the surface. Such a diurnal cycle strongly suggested that this phenomenon was due to migrating marine organisms rather than to a physical discontinuity in the water, such as temperature change. Also, a temperature-change boundary is completely unable to account for the intensity of the scattered sound. It is well known from net hauls that offshore zooplankton, in general, such as the copepods *Calanus finmarchicus* and *Metridia lucens*, pelagic prawns, euphausiids, and many other organisms exhibit marked negative phototropism and that they make daily vertical migrations from the surface to depths as great as 2,500 feet. Presumably, many types of zooplankton migrate to the surface at night to feed in the phytoplankton-rich surface layers and, in the morning, they descend to regions of darkness at great depths, possibly for safety from their predators. However, many marine zooplankton forms may be too small to scatter 18-kilocycle sound effectively. For this reason, it has been suggested that the sound scatterers are nekton, such as fish or squid, which follow and feed upon the zooplankton. Recently, Lyman (1948) has suggested that squid are the scattering organisms. In any case, it is probable that migrating zooplankton are at least indirectly responsible for the D. S. L.

There is comparatively little previous information regarding the geographical distribution of the D. S. L. It is known to be frequently present off the California and Lower California coasts, especially during the day. It has been reported occasionally from various spots in the Pacific. Recently, workers at Woods Hole Oceanographic Institution have reported (personal communication) the presence of this phenomenon in the Atlantic Ocean. Also, it is probable that some reports of uncharted shoals by ships at sea are false bottoms ascribable to the D. S. L.

¹ It has also been suggested that this layer of deep scatterers be called the ECR layer in recognition of the joint discovery by C. F. Eyring, R. J. Christensen, and R. W. Raitt in connection with underwater sound work at the University of California Division of War Research. Other workers who have made important contributions to the study of this phenomenon include C. Eckart, G. E. Duvall, R. Ely, and M. W. Johnson. M. W. Johnson first showed the apparently biological nature of the scattering layer. Most of the studies by these workers are in anonymous wartime reports.

DEEP SCATTERING LAYER OF THE USS HENDERSON
AND USS NEREUS FATHOGRAMS

General Remarks. Prior to a discussion of the HENDERSON and NEREUS tapes, it should be pointed out that the absence of a record of the D. S. L. on the fathogram does not necessarily preclude its presence, because such absence may be due to mistuning or other causes. A low gain setting will fail to bring in the D. S. L.; also, a gain setting which is too high may mask the Layer. Such changes in sensitivity undoubtedly account for its disappearance and reappearance throughout certain days. The Layer may also be masked by background noise produced by the ship when underway or by operation of some of the ship's equipment. However, when it does not show up throughout a long period of time it may be presumed to be absent or at least very poorly developed. Throughout these cruises, the echo sounders were operated primarily to obtain depth information, and the recording of the D. S. L. was incidental. The length of the outgoing sound signal masked any echoes from the D. S. L. when it ascended to depths less than about 100 fathoms on the HENDERSON record and less than about 60 fathoms on that of the NEREUS. The time used throughout this paper is the standard time for the zone in which the ship was located. The NMC echo sounder of the HENDERSON and the NMC-1 fathometer of the NEREUS utilized 18-kilocycle sound pulses.

Deep Scattering Layer during Operation HIGHJUMP. The distribution of the D. S. L. during Operation HIGHJUMP and other cruises is shown in Fig. 1, and its general appearance in Fig. 2. With the exception of two days in the vicinity of the Marquesas Islands, the Layer was recorded the greater part of each day during daylight hours throughout the passage from San Diego to the Antarctic between December 2-23, 1946. Controlled by the length of daylight, the Layer was detected at least discontinuously for as short as a ten-hour period and as long as a 19-hour period. Except in the early morning or the late evening, when the Layer was actively migrating, it was developed at depths from 150 to 450 fathoms. Near San Diego a depth of about 150 to 200 fathoms was characteristic, whereas in the tropical and southern waters a depth of 200 to 350 fathoms was more typical. The ascent and descent of the Layer was closely correlated with sunset and sunrise, respectively. With the exception of one or

Figure 1. Map of the Pacific Ocean showing the distribution of the Deep Scattering Layer along the tracks of the USS HENDERSON and the USS NEREUS. Solid lines indicate the continuous or almost continuous daytime development of the Layer. Dotted lines show the intervals during which indications of the D. S. L. were rare or entirely absent from the fathogram.

two questionable sporadic displays of the D. S. L., it was completely absent from the fathogram during hours of darkness. The phenomenon of a double D. S. L. was frequently displayed.

The Antarctic Convergence was crossed at noon on December 23 in the vicinity of Latitude 62° S. This water mass boundary was clearly indicated by an abrupt drop in temperature from 39 to 33° F. It is noteworthy that the D. S. L. disappeared completely for three days after crossing this boundary and was rarely ever well developed in Antarctic waters.

During the period from December 25 to March 2, the HENDERSON navigated slowly westward along the western Pacific and Indian Ocean sectors of Antarctica. Only a few indications of layers of deep scatterers were recorded for short intervals from December 27 to January 21, which was a period of permanent (or almost permanent) daylight. From January 21 to 29 the D. S. L. was once again well developed and displayed the typical diurnal cycle (Fig. 2). This display might be correlated with the return of a day and night cycle, because by this date there were a few hours of complete darkness. However, subsequent to February 2 the D. S. L. was almost completely absent throughout the remainder of the Antarctic cruise and during the passage to Australia.

During the return passage from Australia to the United States, the D. S. L. was detected on the third day out of Sidney. The typical diurnal cycle was recorded each day until the echo sounder went out of operation at about Latitude 20° S. because of mechanical failure.

Deep Scattering Layer from Hawaii to the Arctic. During the period between July 15 and August 10, 1947, the USS NEREUS made a continuous fathogram from Pearl Harbor to the Arctic with an NMC-1 echo sounder using 18-kilocycle sound pulses. This fathogram shows indications of the development of the D. S. L. each day throughout the cruise whenever the vessel was in deep oceanic water. The shoal depth of the Bering and Chukchi seas precluded the development of a deep layer of scatterers and the fathogram shows no evidence of any layers of scatterers in these areas.

The NEREUS fathogram displays especially well the morning descent and the evening ascent of scatterers. They appear to migrate as a relatively compact layer rather than diffused, but the movement of scatterers in depths less than 60 fathoms cannot be determined because of masking by the outgoing ping. Although the diurnal vertical migration is well displayed, the scatterers descended to a depth so great that throughout most days they were beyond the range of good

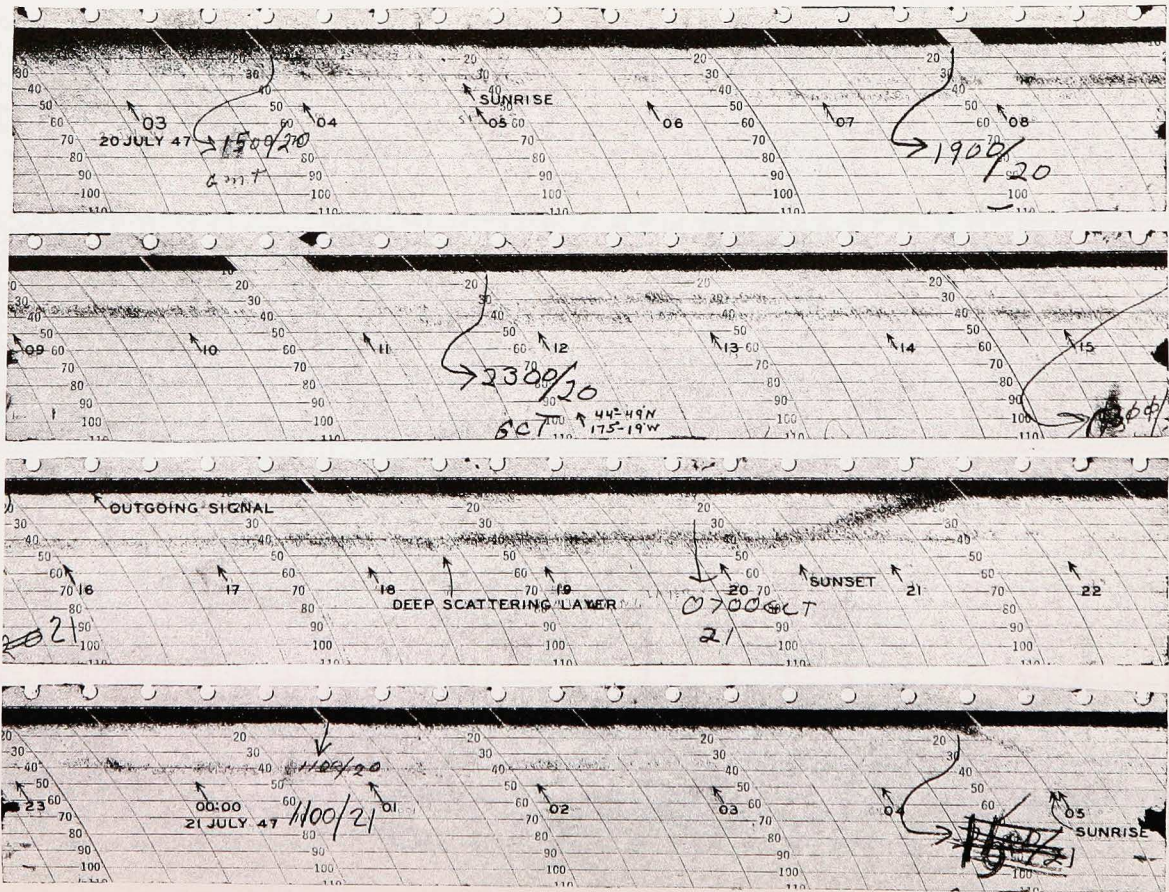


Figure 3

detection by the echo sounder; therefore the D. S. L. was only sporadically recorded.

On July 20 at noon position of Latitude $44^{\circ} 49' N.$, Longitude $175^{\circ} 19' W.$, the Layer was prominently developed throughout the entire day (Fig. 3). This comparatively strong development of the Layer may have been caused by a higher concentration of scattering organisms in the productive waters of the Aleutian (Subarctic) Current which lies between Latitude $42^{\circ} N.$ and the Aleutian Islands. The development of the D. S. L. at depths from 175 to 225 fathoms was in agreement with depths observed elsewhere. Twice during this day, a double D. S. L. appeared. It was especially surprising that, although a portion of the scatterers rose at sunset, the rest remained at a depth of 175 fathoms throughout the night. Although the other tapes examined occasionally show sporadic indications of a scattering layer at night, this was the only record of a prominent and continuous D. S. L. throughout most of the night.

Another interesting phenomenon noted only on the NEREUS fathogram was the presence of a double layer descending each morning during the period from July 15 to 18. These double descending layers were separated by a time interval of about 20 minutes and apparently were the result of the downward migrations of two types of organisms that are negatively phototropic to markedly different degrees. Yet, at sunset of these same days only a single ascending layer was noted.

The vertical migrations were so clearly defined on the NEREUS tape that it was possible to measure roughly the rate of ascent and descent. In the morning the scatterers appear to descend at a rate of about 10 to 15 feet per minute. The evening ascent was slightly more rapid and was accomplished at a rate of about 15 to 18 feet per minute.

In agreement with all other observations, the D. S. L. was almost entirely a daytime phenomenon, and the vertical migrations were closely correlated with sunrise and sunset or, more exactly, with the beginning and end of a certain, but unknown, amount of twilight. The descent, deeper than 50 fathoms, began about one hour before sunrise, attained its maximum depth shortly after sunrise and varied only slightly throughout the day. The evening ascent began shortly before sunset but did not reach the 50-fathom depth until about one hour after sunset. Just what became of the layer at depths shoaler

Figure 3. Development of the Deep Scattering Layer in the North Pacific on July 20 and 21, 1947 at 150 to 175 fathoms (indicated depth scale should be increased by a factor of five). Note descent of the scatterers beginning before sunrise to form the D. S. L., and the ascent beginning shortly before sunset but not reaching the 60-fathom line until well after sunset. Note also the development of double Layers at 0700 and 1300 hours. Although most of the scatterers rise with nightfall, this fathogram shows the *unusual* development of a D. S. L. throughout the night.

than 50 fathoms is not known, because any further rise of the layer was masked by the outgoing signal. However, prominent extension of the outgoing signal during hours of darkness indicated the abundance of scatterers in the upper 50 fathoms of water.

Deep Scattering Layer from United States to Japan. During the period from August 11 to September 1, 1947, the USS HENDERSON obtained a fathogram across the Pacific Ocean with a recording NMC echo sounder from San Diego, California to Yokoshuka, Japan via Pearl Harbor, Hawaii. Although the echo sounder was operating erratically most of the time, resulting in a poor fathogram, the D. S. L. can be at least sporadically detected almost every day at various times during daylight hours. From the fathogram it appears probable that a properly working and sufficiently sensitive echo sounder would have recorded a daytime development of the D. S. L. essentially continuously across the Pacific.

When the vertical migration of the Layer was clearly recorded, it invariably began to descend about one-half hour or more before sunrise and to rise shortly before sunset; however, the upward migration was not completed until after sunset. Multiple layers were occasionally present and the scatterers were located at a depth of between 150 and 250 fathoms.

During the first half of the San Diego to Pearl Harbor passage, the D. S. L. was present during portions of each day at a depth of from 175 to 250 fathoms. Due to mechanical failure, the echo sounder was not in operation during the last half of this passage.

After leaving Pearl Harbor, the Layer was fairly well developed the first day out of port. During the next two days, it was not detected. Yet, from the fourth day out of port until arriving in the shallow water off Japan, five days later, the D. S. L. was recorded every day and it appeared to become more strongly developed with westward penetration.

DISCUSSION

Examination of three fathograms which cross the Pacific in both a north-south and an east-west direction, and cover a sector of the Antarctic Ocean as well, shows a wide development of the Deep Scattering Layer. It appears to be an oceanic phenomenon which is Pacific-wide and probably world-wide.

All of these records further substantiate the diurnal cycle by which the scatterers descend in the morning and ascend to near the surface at night. Judging from the NEREUS fathograms, the scatterers begin their descent about one hour before sunrise and they do not complete

their ascent until about one hour after sunset, so that they are in the surface waters only during rather complete darkness. Apparently the scatterers are motivated by a small amount of light, so that the migrations are actually correlated with a certain amount of twilight rather than with sunrise and sunset. No information was obtained on the distribution of scatterers in the surface water at night because of masking by the outgoing ping.

Because of the diurnal cycle, it is evident that the D. S. L. is a biological phenomenon so that the scattering agents must be zooplankton, nekton, or bubbles associated with such organisms. Yet, from these records no definite conclusion can be drawn as to whether zooplankton or fish cause the scattering. It will be necessary to make numerous laboratory experiments on the scattering characteristics of the various forms and to correlate underwater sound data with net hauls before the nature of the scatterers can be established. However, the extensive distribution of the D. S. L. is suggestive of zooplankton, and the comparatively slow speed of migration of the scatterers as a layer is, perhaps, also more suggestive of the general zooplankton than of faster swimming fish. The occasional development of night layers, of double descending layers, and of multiple deep layers of scatterers show that the phenomenon is complicated and probably involves many kinds of organisms and/or different stages of development of a single species.

The amount of scattering is dependent in part on the sum of the cross sections of all the objects present. The total mass of zooplankton in the ocean is many times the mass of fish. Also, since the mass of a body varies as the cube of any linear dimension, whereas the surface varies as the square, a given mass of small organisms such as zooplankton present a much greater surface from which scattering might take place than an equal mass of fish. Thus, the extensive and frequently continuous distribution of the D. S. L. suggests that pelagic zooplankton may be the basic cause of the phenomenon. Yet, if zooplankton scatter sound like solid or liquid particles, most of them are too small to be effective scatterers of 18-kilocycle sound, which has a wave length of about three inches in water, because the scattering efficiency of an object smaller than the wave length is proportional to $(d / \lambda)^4$, where λ is the wave length of the sound signal and d is the circumference of the scattering object. Therefore, solid or liquid particles are inefficient scatterers if less than about one inch, and consequently an unreasonably high concentration of such organisms is required to produce the observed scattering. Also, the intensity of the scattering from small organisms is highly dependent upon the frequency of the sound, but such frequency dependence has been shown

not to exist in work off California. Thus, although the small zooplankton such as the copepods are probably not the scatterers, larger forms such as the euphausiids, which often reach the length of about one inch, may possibly cause the scattering.

Very small air bubbles in water are known to be excellent scatterers of sound, because a gas has a markedly different density and compressibility than water. For this reason, gas bubbles have an "effective diameter" for scattering sound of many times their actual diameter. Scattering is especially great if the bubble is of a certain critical size so that it is resonant. The diameter of a resonant air bubble in water for 18-kilocycle sound is about 1.5 mm. at 150 fathoms, about 2.0 at 265 fathoms, and 2.5 at 415 fathoms. The size of a resonant gas bubble enclosed in a marine organism would vary somewhat from these figures because it would depend upon the elastic properties of the organism and the type of gas. In any event, if minute bubbles are enclosed in the migrating organisms, or if they are excreted by these organisms and exist for a short interval before being dissolved, they would probably adequately account for the phenomenon of deep scattering. However, there is no record of the presence of such bubbles in vertically migrating types of pelagic organisms.

As might be expected, there appears to be some correlation between the depth of the D. S. L. and factors which control the depth penetration of light. For example, previous observations (Anon., 1946a) in coastal water off California showed the characteristic depth to be about 150 to 250 fathoms. A similar depth was observed off California on the HENDERSON records. However, in the oceanic tropical and subtropical Pacific, under conditions of highly transparent water and an overhead sun, the D. S. L. was typically at a depth of from 250 to 350 fathoms. No good correlation was detected between the amount of cloud cover and the depth of the Layer.

An interesting question to consider is, What effect does the continuous daylight of polar midsummer have upon the diurnal cycle of the scatterers? From the HENDERSON fathogram it appears that the D. S. L. generally does not form under conditions of permanent or almost permanent daylight. Yet, weakly developed and questionable layers of deep scatterers were sporadically present. In this connection, net haul studies of plankton by Bogorov (1946) are noteworthy. According to his studies, zooplankton in the Barents Sea (Lat. 75° N.) under conditions of permanent daylight do not perform the regular vertical migrations that are characteristic of zooplankton of lower latitudes, but rather they maintain an almost unchanged vertical distribution throughout a 24-hour period. Further south in the White Sea (Lat. 65° N.) Bogorov noted the presence of a mixture of

both the usual migrating types and the Polar non-migrating types of zooplankton.

Correlated with the return of a day-night cycle in the Antarctic towards the end of January, the diurnal migrating of the scatterers and the development of a D. S. L. was once again detected. However, in this connection the almost complete absence of the Layer during both February and the first part of March is puzzling and without a reasonable explanation.

Investigation of the D. S. L. is a fertile field for research. This phenomenon is of importance in connection with the transmission of underwater sound. If the scatterers are fish, even in part, a study of the Layer is of obvious direct commercial value. If the scatterers are zooplankton, much can be learned about these organisms concerning their habits and distribution. Also, if measurements are made under controlled conditions so that a scattering coefficient can be obtained, roughly quantitative data concerning the populations of the scatterers might be obtained. A study of the variation of the amount of scattering with sound pulses of various frequency would yield information on the size of the scatterers.

SUMMARY

Examination of almost continuous fathograms from California to the Antarctic, from Hawaii to the Arctic, and from California to Japan revealed a Pacific-wide distribution of the Deep Scattering Layer at various depths between 150 and 450 fathoms during daylight. As previous workers have noted, the D. S. L. is formed by scatterers that descend in the morning from near the surface and ascend in the evening. This diurnal cycle indicates that this phenomenon is produced by the vertical migrations of organisms rather than by a purely physical discontinuity. No direct evidence was obtained to determine whether the scatterers are zooplankton or larger forms such as fish. However, certain indirect evidence, such as the extensive and continuous distribution and the method of migration, is more suggestive of zooplankton.²

Although generally a daylight phenomenon, the D. S. L. was present throughout one night in the North Pacific. Double descending layers of scatterers were occasionally observed in the morning and multiple

² Since completing this paper and submitting it for publication, the writer has performed an experiment which shows that even very minute particles, when present in clouds, can strongly scatter high frequency sound. Sand clouds, made by pouring a bucket of fine sand (median diameter of 0.5 mm) into the ocean, have been observed to effectively scatter 18-kilocycle sound of an NMC-1 echo sounder down to at least 60 fathoms. Hence, it is likely that swarms of even the smallest zooplankton can account for the D. S. L.

deep layers are common, suggesting that many kinds, and/or developmental stages, of organisms are involved.

Controlled by the length of daylight, the D. S. L. was developed for as little as 10 hours per day and as much as 19 hours in high latitudes. Generally the D. S. L. did not appear to form during the period of permanent or almost permanent daylight of the Antarctic midsummer. Further investigation of this phenomenon promises to yield information of important scientific and commercial value.

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