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Polarization of scattered sunlight in deep water*

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Summary—1. Photographic measurements of the polarization pattern of underwater illumination were made at depths of 30, 60, 100, 150, and 200 m in oceanic water with a vertical extinction coefficient corresponding to Secchi disc readings between 22–26 m. A special polarization analyzer, attached to the outside of a deep-sea camera case, provided in a single photograph direct evidence for: (a) presence or absence of polarization with a high degree of sensitivity; (b) type of polarization; (c) plane of polarization, if linear; (d) rough comparative indication of the degree of polarization. By photographing the interference pattern formed by this analyzer when traversed by polarized light, records of the polarization of horizontally scattered sunlight were obtained in four azimuths relative to the sun's bearing: 0°, 90°, 180°, 270°, at eleven different stations, including two at each depth except 200 m.

2. Horizontally scattered light was found to be polarized at all depths, 200 m included, and in all directions tested; the type of polarization was linear in every instance. In so far as could be judged from the photographs (Fig. 3), the percentage polarization at 200 m appeared to be at least as great as at lesser depths.

3. The plane of polarization was always horizontal in lines of sight toward and away from the sun's bearing but was tilted toward the sun in azimuth's normal to these; this effect of the sun's position was still considerable at 200 m. The amount of tilting occurring in lines of sight 90° from the sun's bearing was primarily related to the angle of refraction for sunlight at the air–water interface (Fig. 2), but a second effect, resulting from depth of light penetration, was shown by the decrease in the tilting of the polarization plane as depth was increased.

4. It is concluded that: (a) scattered sunlight underwater is linearly polarized to considerable depths, probably throughout the photic zone; (b) the pattern of polarization is dependent on the sun's position at least to a depth of 200 m and (c) such optical phenomena therefore may be important in the behaviour of photic zone bathypelagic animals as well as epipelagic forms.

INTRODUCTION

PREVIOUS MEASUREMENTS (WATERMAN, 1954 A) have shown that natural underwater illumination is linearly polarized in patterns which seem basically similar to those of the blue sky.† This is true of the upper 15 m or so of water to which the earlier work was limited. Since the most probable origin for this polarization would appear to be the molecular or fine particle scattering of directional light rays penetrating the water, it was predicted that linear polarization of submarine illumination should occur as deep as significant amounts of directional light are transmitted. It was also indicated that, since certain terrestrial and shallow water animals are known to be capable of utilizing polarized light in the sky for their orientation and navigation, underwater polarization may prove to be a factor of considerable ecological importance

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† This introductory statement refers only to polarization arising within the water itself. It does not include the direct underwater observation or measurement of polarized sky light. The known relation between these two sources of polarization has previously been described for shallow water (WATERMAN, 1954 A). Further measurements will be required to establish in deeper water the effective penetration and influence of polarized sky light, as opposed to direct sunlight, which is unpolarized in the atmosphere.

in the location and migration of animals of the whole photic zone. For these reasons the extension of our knowledge of submarine polarized light into deep water is a matter relevant to several points of interest.

The present report describes the results of photographic polarization measurements down to 200 m which extend our information to depths in excess of ten times those previously studied. It clearly proves that polarization of sunlight under water is not merely a superficial phenomenon but one which also must be reckoned with at considerable depths.

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EQUIPMENT AND PROCEDURE

The data reported here were obtained in the southwest North Atlantic just west and northwest of Bridgetown, Barbados, B.W.I. (13° N, 59° W) working from R.V. *Atlantis*. Polarization measurements were made at 30, 60, 100, 150 and 200 m. The average echo-sounding depth at the various stations was about 1,200 m so that no effect of reflection or light scattering by the bottom could reasonably have influenced the results.

Secchi disc readings ranged from 22–26 m, indicating moderately clear oceanic water in the upper layers. These depths correspond to vertical extinction coefficients of about 0·055–0·065 (Clarke, 1941), or to overall transparency between Jerlov's (1951) types I and II oceanic water. The sea was moderate (Beaufort 2–3), confused and occasionally had a large swell during the work.

While the measurements were being made, the sun was shining on the sea surface in all cases, although as work progressed on the 200 m station (No. 11), a high thin overcast slowly cut down the direct sunlight from full to a point where shadows were just visible. In all other cases the sky was either mainly clear overhead or nearly completely clear. Stations were made at various sun's altitudes from 26–52°. The latter was close to the local noon maximum for the period around December 1 when this work was done.

In order that the results obtained may be effectively presented, the optical equipment used and the procedure for making the measurements will first be described.

The basic units of equipment employed were (1) a special polarization analyzer and (2) a camera. The latter was arranged to record the interference figure produced by the analyzer when it was traversed by polarized light. This analyzer, which has been used before for visual observations (Waterman, 1954 a) is made up of two essential optic components. The first of these is a calcite crystal about 3·5 mm thick cut at right angles to its optic axis; the second is a circular polarization analyzer. This consists of a quarter wave plate and a linear polarizer in that order with the slow axis of the former oriented 45° clockwise from the transmitting axis of the latter.

When convergent polarized light passes through this optic system, an interference pattern is formed. Four parameters of the pattern are directly dependent on the properties of the light traversing the analyzer. The figure's contrast and extent depend roughly on the intensity and percent polarization of the incident light. Its colour is related to the wavelengths transmitted. Finally, the geometry of the interference figure varies with different kinds of polarized light whether linear, elliptical or circular.

Such patterns arise because light rays in the convergent beam which pass through the crystal plate obliquely, i.e., not parallel to its optic axis, will be split up into two rays by the calcite's birefringence. These undergo different retardations in passing through the crystal. On emerging from it and traversing the circular analyzer, they form areas of cancellation and reinforcement in a radially symmetrical pattern whose relative size depends on the thickness and birefringence of the crystal.

With monochromatic polarized light the interference pattern consists of alternating dark and light concentric rings, successive light areas of the pattern corresponding to differences of one wave-length in the oblique ray paths through the calcite. With white light a series of brilliant interference colours in isochromatic rings will be added to this basic pattern.

If the light entering the analyzer is circularly polarized, the interference figure obtained under the conditions specified will be a series of complete circular isochromatic curves, starting from a white centre spot and becoming closer and closer together in the higher order rings (Fig. 1A). With elliptically polarized light these rings are distorted into a series of ellipses.

The interference figure produced by linearly polarized light is broken up into four quadrants at the limits of which the isochromatic rings are interrupted and displaced radially. In two diametric quadrants the arcs are moved outward and two dark spots appear in their central sectors (Fig. 1B); in the other sectors the arcs are displaced inward and the centre remains white.

The breaks in the concentric rings are parallel to the *e* and *h* vectors of the linearly polarized incident light. With a negative analyzer crystal, like calcite, and the circular analyzer axes set as described, the *e* vector will be parallel to the breaks which delimit the clockwise edges of the two dark centre sectors.

It should be emphasized that this type of analyzer, although simple, has several important advantages in an application like the present one. Unlike any other polarization analyzer, the present device provides the maximum information of which it is capable without the need of rotating it or moving any of its parts. The plane of linearly polarized light can be observed directly by inspection regardless of the angular relation between the plane of the incident light and the axes of the conjoined quarter wave plate and the linear polarizer.

This is true only when the latter two units are oriented relative to each other as specified. If their axes are not aligned at 45°, or if only a linear analyzer is used with the calcite crystal, the interference figure will change with the rotation of the analyzer. As this happens, a dark cross-like isogyre will be superimposed on the isochromatic lines. Its position and intensity will depend on the relation of the analyzer axis to the plane of incident light polarization. Hence the *e* vector cannot be recognized directly by inspection without rotating the instrument.

Another important property of the analyzer described lies in its high sensitivity. Small percentages of polarization of the order of 5% may readily be detected. The instrument has, therefore, proved useful in addition to its present application in monitoring the illumination of experimental apparatus where polarization of the light source or stray polarized light in the system had to be avoided (WATERMAN, 1950; 1954 B).

It is of interest that, although interference patterns provide a standard means of structural analysis in crystallography, their application in the present instance reverses the known and unknown factors in the optical parameters. In the measurements here described it is not the crystal plate whose characteristics are to be determined but rather the polarization of the deep-sea illumination which traverses it.

A further convenient property of the polarization analyzer used is the fact that the interference figure is optically located at infinity. Consequently the instrument may be fastened directly over the lens of a camera focussed at its principle focus and a record obtained which indicates whether or not polarized light is present or not, even in small amounts. Its type and plane, if it is linearly polarized, will likewise be recorded with precision.

A complication is introduced for deep-sea work, however, by the need for enclosing the camera in a water-proof case whose window is almost certain to exhibit strain birefringence when subjected to pressure. Such an effect was actually observed in some preliminary photographs taken at about 30 m depth with a hand-held camera.*
In that instance the camera with the analyzer attached over the lens was protected in a transparent plastic box. This was apparently birefringent when the pictures were taken since the figure recorded showed elliptical polarization in the horizontal light pattern. Such has never been observed visually under water in level lines of sight (WATERMAN, 1954 A) nor was it ever found in deep water photographs where the possibility of strain birefringence had been eliminated.

To obviate this difficulty in the present instance the analyzer was mounted outside the pressure case enclosing the camera. Both front and back of the optical sandwich involved were thus exposed to equal pressures. No detectable effect of the hydrostatic pressure itself (about 20 atmospheres at the deepest station) was ever observed. Of course, any strain birefringence arising in the window through which the camera looked out of its case would have no effect in this situation since it occurred between the analyzer and the lens.

The camera employed was a 35 mm Robot with an f 2·8 Zeiss tessar lens. It was arranged to be triggered by a solenoid controlled from the ship. After each exposure the film was automatically advanced by the camera mechanism so that 15–20 pictures could be taken on a single lowering of the apparatus. The Robot was mounted in a Ewing-type deep-sea camera case sealed with an O-ring. The lens was aligned with a plane glass window outside of which the polarization analyzer was attached as already described. A two-conductor insulated cable ran from the solenoid operating the camera shutter to the deck laboratory of *Atlantis* where the exposures were controlled.

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The whole deep-sea camera and case were mounted on a weighted frame suspended from the end of the ship's hydrographic cable. When the equipment was lowered into the water, the camera lens and interference analyzer were quite accurately directed horizontally. This was so even while the ship was steaming ahead at slow speeds, a fact which was checked by diving with the ship under way. Consequently the frame of the photographic negatives has been taken as the vertical and horizontal reference for analysis of the data.

Previous work (Waterman, 1954 a) had shown that the intensity and plane of the polarization of underwater illumination were dependent on the relation between the line of sight and the bearing of the sun. Consequently, it was important for the present deep-water measurements to control the azimuth in which the pictures of the polarization pattern were taken. To do so a large fin of sheet aluminum was attached to the frame holding the camera in such a way that the horizontal direction in which the camera would point coincided with the ship's heading.

The procedure used in obtaining the photographic data was as follows. The camera, loaded with Eastman Kodak Tri-X film, which has an American Standards Exposure Index of 200, was lowered to the depth desired. Then the ship steamed slowly ahead in the sun's azimuth, a manoeuvre which would shortly bring the camera's direction of view into alignment with the sun's bearing. After a period which experience with the resulting negatives showed was adequate for the slowly towed camera to settle into this orientation, a series of three exposures was made separated by 5 second intervals.

Exposure times and diaphragm stops were first set on the basis of the estimated extinction coefficients of the water mass concerned, then, if necessary, corrected from experience. No photometric transparency measurements were made, but an approximate value was obtained for the surface layers by the use of the Secchi disc at each station (Clarke, 1941) and by comparison with published data from stations made in nearby areas (Jerlov, 1951). Actual exposures used varied with the sun's altitude as well as depth of the camera from 1/25 sec at f/4 for 30 m to 20 sec at f/2·8 for 200 m.

After pictures had been taken in one direction, the ship's course was altered 90° clockwise, and after a suitable wait of about 5–10 min for the camera and cable to swing around, another three photographs were made, this time looking 90° to the right of the sun's azimuth. Similarly two more sets of exposures were made in directions 180° and 270° to the right of the sun's bearing.

It should be mentioned that because of the wind (force 3–4 Beaufort) and sea running at the various stations, it was not always possible to obtain records under ideal conditions for each of the four azimuths tested. In some cases the wire angle instead of being negligible was appreciable, particularly for downwind or crosswind legs of the station. Similarly the behvaiour of the cable after a turn sometimes showed that the apparatus was slow in aligning its heading with that of the ship. Reasonable compromises between ideal recording conditions and practical handling circumstances of the ship and gear had therefore to be made.

In the absence of a more elaborate apparatus where the camera's direction could be immediately and accurately controlled from the surface and monitored with repeating compass and precise vertical reference, the reliability of the present results could be insured only by the care and experience exercised in carrying out the manoeuvres described. It could be checked, however, by the consistency of the data obtained, both internally and with reference to relations indicated by previous shallow-water observations.

A total of 11 stations were made. Of these the first 4 and No. 6 showed considerable internal inconsistencies for azimuth, apparently arising from inexperience with difficulties like those outlined. But on the basis of their coherence, the data for the remaining 6 stations indicate that such interference had been minimized. These include one set of records each at 30, 60, 100, 200 m and two at 150 m.

RESULTS

The data of these measurements provide information relevant to four or five different aspects of the general problem.

In the first place every photograph taken during the present deep-water series showed a well-developed interference figure (Figs. 2, 3). This proved that the scattered horizontal underwater illumination in the directions photographed was polarized at all depths tested including the deepest, 200 m. Furthermore, as the interference pattern clearly consisted of four quadrants of isochromatic curves made up of broken concentric rings with two diametrically opposite dark central sectors, this light must have been linearly polarized.

Table I

Station No. 9	13° 08′ N, 59° 50·5′ W.	Dec. 2, 1954
Sun's altitude: 34° 40′		Sun's azimuth: 129°
Angle of sunlight incidence: 55°		Calculated angle of refraction: 38°
Depth of measurements: 60 m		Depth to bottom: 1150 m

Direction relative to sun's bearing	0°	90°	180	270
Tilt of polarization plane				
Exposure ♯ 1	0°	17° left	1·5 left	11 right
♯ 2	1° right	19° left	2·0 left	16 right
♯ 3	0°	—	2·0 left	19 right
Average	0·3° right	18° left	1·8 left	15·3 right

Although the method of polarized light analysis employed does not permit any close estimate of percentage polarization, there is some evidence pertinent to this matter in the photographs. In so far as it can be gauged by the intensity and extent of the interference pattern photographed, the degree of light polarization at 200 m seemed to be about as great as at any shallower depths. The number of concentric isochromatic rings recorded at this deepest station is fully as large as at any other in the present series.

Also it is clear from the same kind of evidence that in deeper water there is no marked change in percent polarization with direction of view relative to the sun's azimuth. In fact No. 8 at 30 m (Fig. 2) was the only station obviously providing evidence for this relation which was always found visually in shallow water (Waterman, 1954 a).

On the other hand, the effect of the relative bearing of the sun on the plane of polarization was a prominent and highly significant feature of the records at all stations. This is exemplified by the data for stations 9 and 11 which are presented in Tables I and II and by Figs. 2 and 3 for stations 8 and 11.

In general the *e* vector of the polarization was horizontal in the sun's and the anti-sun's bearings but was tilted towards the sun at azimuths normal to these lines of sight. When the polarization plane appeared to be tilted in bearings towards or away from the sun, it has been assumed that this was the result of the camera not being precisely horizontal or pointing accurately along the ship's heading as discussed under procedure. The magnitude of these influences, obvious in the directions cited, should in addition give some information on the reliability of the measurements made normal to the sun's azimuth where the present data do not otherwise provide any estimate of variance.

The tables and photographs illustrate two important points inherent in the total data. First is that the sun's position influenced the pattern of submarine polarization at all depths so far studied, including 200 m, the deepest of the present stations, and the shallow water observations made previously. The optical effects involved here were (1) the angle of refraction of the incident rays of sunlight and (2) the apparent origin of underwater polarization from primary Rayleigh scattering of directional light beams, which causes the polarization plane to be normal to the angle of refraction.

Table II

Station No. 11	13° 07′ N, 59° 53′ W.	Dec. 2, 1954
Sun's altitude: 51° 40′		Sun's azimuth: 201°
Angle of sunlight incidence: 38°		Calculated angle of refraction: 27°
Depth of measurements: 200 m		Depth to bottom: ——

Direction relative to sun's bearing	0°	90°	180°	270°
Tilt of polarization plane Exposure ♯1	0°	7·5° left	0°	11° right
♯2	0·5° left	7·5° left	0°	7·5° right
♯3	1° left	7·0° left	—	8·5° right
Average	0·5° left	7·3° left	0°	9·0° right

This effect was certainly predominant in shallow water. It was also at the 30 m station (No. 8) in the present series (Fig. 2). Here the tilt of the polarization plane averaged 43° for lines of sight normal to the sun's bearing. This angle was almost identical with the corresponding angle of refraction (42°) calculated from the observed solar altitude, assuming a refractive index for the water of 1·34.

Such an effect of the sun's altitude, and hence the angle of refraction of sunlight entering the water, must also be involved in the plane of polarization at greater depths, too. Yet the present data do not afford much direct evidence for this since repeated measurements were not made systematically at the same depth with different solar altitudes. However, in the single satisfactory case where such a comparison can be made, strong support for this generalization is found. This comes from the data of stations 7 and 10, both at 150 m.

Here the angles of refraction of sunlight, computed from the sun's elevations, were not the same because of the different times of day when the two sets of photographs were made. It will be seen in Table III that the deviations of the polarization planes

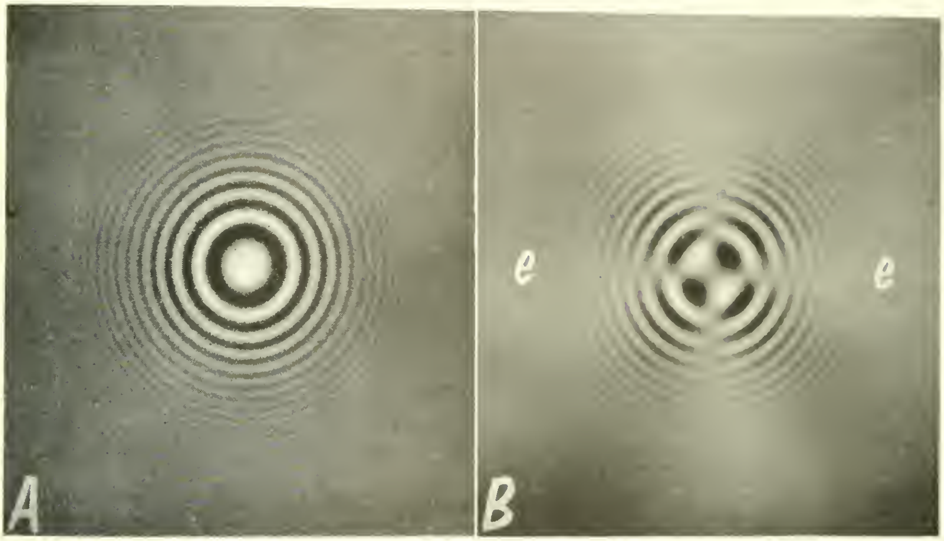

Fig. 1. Interference patterns formed by the analyzer when traversed by polarized light. *A.* Figure produced by circularly polarized light having a counterclockwise rotation: if its rotation were clockwise, the pattern would have a dark centre instead of a light one. *B.* Figure observed with linearly polarized light produced by a type H Polaroid filter. The interruptions in the isochromatic rings are parallel to the electric and magnetic vectors of the incident light. The plane of the *e* vector is horizontal, as labelled, and coincides with the clockwise edge of the dark central sectors.

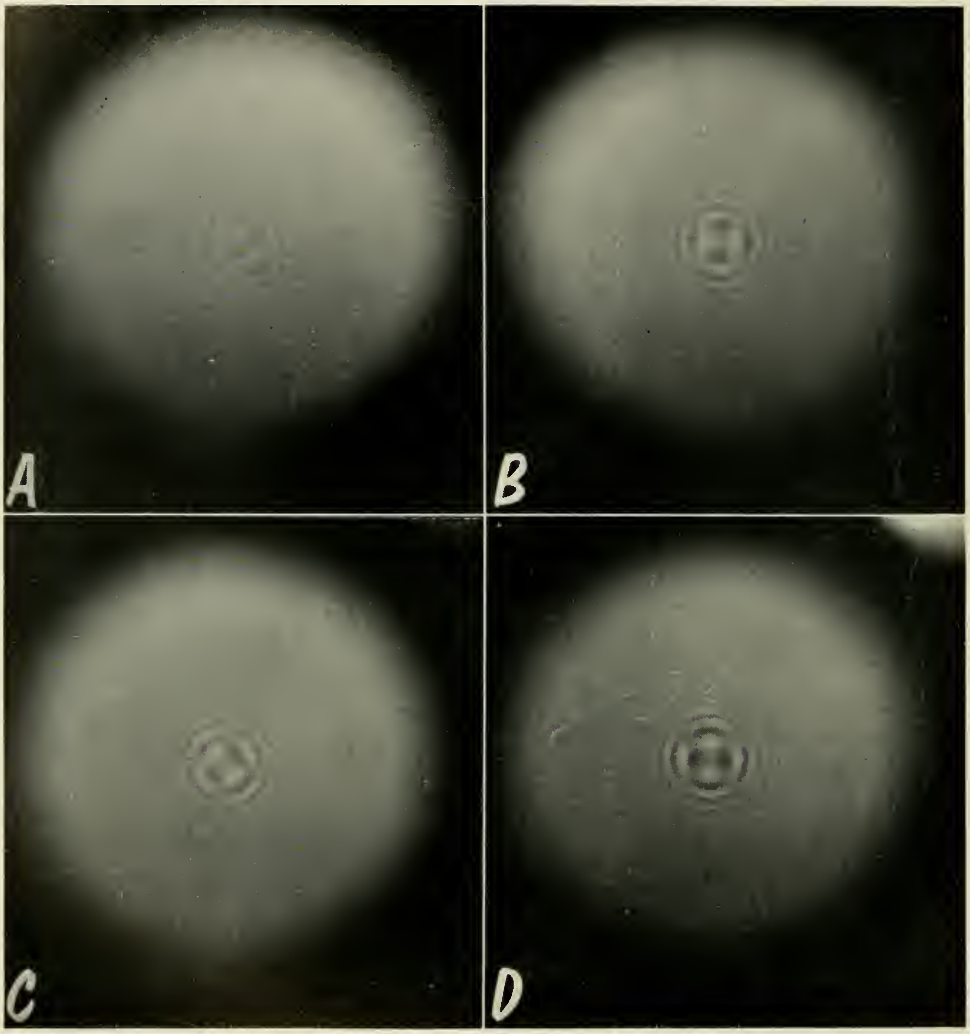

Fig. 2. Interference patterns formed by natural light underwater at 30 m depth (station 8). The analyzer and camera were directed horizontally in azimuths of (*A*) 0°, (*B*) 90°, (*C*) 180°, and (*D*) 270° relative to the sun's bearing. The scattered sunlight is seen to be linearly polarized in all cases, with the polarization apparently weakest at 0° (*A*) and stronger particularly at 90° (*B*) and 270° (*D*). The planes of polarization (angles between plane of light vibration relative to the horizontal) measured in uncropped prints where the film frames provide the vertical and horizontal references were: (*A*) 8·5° tilt toward the right, (*B*) 42·5° left, (*C*) 4° right and (*D*) 43° right. Exposures: $\frac{1}{2}$ sec, f/4, Tri-X film. Sun's altitude 26°.

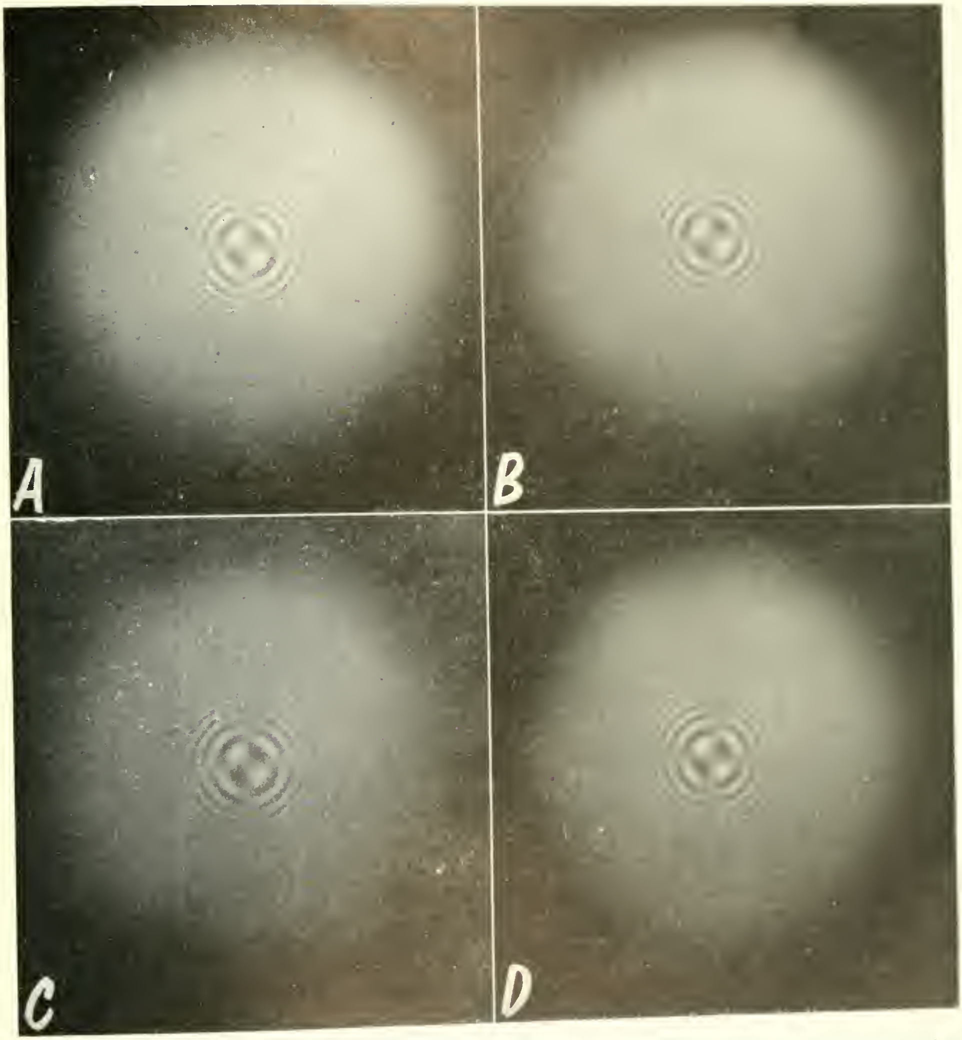

Fig. 3. Interference patterns formed by natural light underwater at 200 m depth (station 11; for the complete protocol see Table II). The analyzer and camera were directed horizontally in azimuths of (*A*) 0°, (*B*) 90°, (*C*) 180° and (*D*) 270° relative to the sun's bearing. The scattered sunlight is seen to be linearly polarized in all cases with the polarization apparently of comparable intensities in all directions. Implied by the extent and contrast of the pattern is the fact that polarization is still considerable even at this depth. The planes of polarization (angles between the planes of light vibration and the horizontal) measured in uncropped prints where the film frames provide the vertical and horizontal references were: (*A*) 0·5° tilt toward the left (*B*) 7·5° left, (*C*) 0° (no tilt) and (*D*) 8·5° right. Exposures: 20 sec, f 2·8, Tri-X film. Sun's altitude 52°

from horizontal were correspondingly different even though they do not agree numerically with the angles of refraction. Note, however, that the ratios of the observed angles to the calculated ones were more nearly alike. In other words, the observed angles of polarization deviated significantly from those calculated simply on the basis of surface refraction. This introduces the second point illustrated by Tables I, II, and Figs. 2, 3.

The second point is the effect of depth *per se* on the tilt of the polarization plane independent of the solar altitude. This influence was obvious in the data of all the stations deeper than 30 m. At 200 m (Table II), for example, the average tilt of the polarization plane 90° from the sun's azimuth was 8°, which was only 30% of the angle of refraction of the sunlight at the surface when the photographs were made. For the stations at intermediate depths, the tilt of the polarization plane was also intermediate, being significantly less than the angle of refraction yet considerably larger than the tilt found at 200 m.

Table III

Station	*Sun's altitude*	*Calculated angle of refraction* (r)	*Polarization tilt* (p)	p/r %
7	30°	40°	15·5	39%
10	52°	27°	11·6	43%

DISCUSSION

The new facts which have been presented above are mainly of interest for two reasons. One is their possible usefulness in solving physical optic problems relating to underwater polarization in particular and to light penetration in general. The other is their potential helpfulness in evaluating the biological importance of submarine polarization patterns.

With relation to the first point, it is interesting that two of the main findings reported here were predicted on a theoretical basis before the present measurements were made (WATERMAN, 1954 A). These were (1) that polarized light would occur down to considerable depths in the sea, probably as far as the lower limits of the photic zone, and (2) that with increasing depth the influence of the sun's position on the pattern of polarization would gradually diminish in the upper few hundred metres after which it would be negligible. Both of these effects were clearly apparent in the present data; although at the maximum depth tested, 200 m, the sun's position still had considerable effect, it was only about a third of what it would have been near the surface.

Note that these predictions were made on the assumption that Rayleigh scattering of unpolarized directional light in the water was the basis of the primary underwater polarization pattern and on the currently accepted ideas about the directionality of deep-water illumination (WHITNEY, 1941; POOLE, 1945; JERLOV, 1951). The fact that the deep polarization as it was actually found matched the predictions in these respects is in turn putative evidence for the validity of these elements in the original analysis.

One might go a step further here and point out that, when the submarine polarization pattern itself is understood more thoroughly, instrumentation and methods like those used in this work might be a convenient way to study the general problems of directionality and scattering of light under water. For instance, one might study the refractive effect of abrupt density changes where these are inaccessible for direct observation (LIMBAUGH and RECHNITZER, 1955).

As to their biological interest, the present results would seem to be significant because they greatly extend the known regions in which those animals whose eyes are sensitive to them might detect natural patterns of underwater polarization. This would now seem to be indicated for a good part, if not all, of the photic zone. Similarly, the possibility of some sort of a polarized light sun compass, comparable to that used in the sky by bees, and other animals, has been extended under water at least to 200 m, since changes in the sun's position result in corresponding modifications of the polarization pattern that far down.

Of the several fields in which further research on the subject of underwater polarization and its significance may be profitable, the most interesting one related to the present deep-sea work would be the possibility of making measurements at still greater depths. Since a 20 sec exposure at f/2·8 was required to photograph the interference pattern at 200 m, the present method was being pushed close to its reasonable limit. This is obvious from the fact that the light energy penetrating the water mass would probably be reduced to 0·1 its value at 200 m by an additional 40–50 m of water. Hence to go from 200 m to 300 m would require 100 × as much time for comparable negative densities!

On the other hand, since directionality of penetrating light is maintained to the lower limit of the photic zone, even though obliquity is decreased eventually to zero, somewhat deeper measurements should be possible if the polarization pattern were photographed in an upward direction. At least the light intensity would be greater to a degree dependent on the relation between scattering and absorption in the water mass concerned (PETTIT, 1936; ATKINS and POOLE, 1952). However, the percent polarization due to Rayleigh scattering would approach zero along the axis of the directional light beam so that the interference figure would become weak or disappear.

In any case it would be desirable to attempt such measurements and discover which of the various factors are actually critical under these circumstances. The presence of upwardly directed " telescopic " eyes in some bathypelagic fishes like *Opisthoproctus* and *Argyropelecus* is suggestive of the biological importance of vertical illumination in deep water.

REFERENCES

ATKINS, W. R. G. and POOLE, H. H. (1952), An experimental study of the scattering of light by natural waters. *Proc. Roy. Soc., London*, B, **140**, 321–338.

CLARKE, G. L. (1941), Observations on transparency in the southwestern section of the North Atlantic Ocean. *J. Mar. Res.*, **4**, 221–230.

JERLOV, N. G. (1951), Optical studies of ocean waters. *Rept. Swedish Deep-Sea Exped.*, 1947–1948, **3** (1), 1–59.

LIMBAUGH, C. and RECHNITZER, A. B. (1955), Visual detection of temperature-density discontinuities in water by diving. *Science*, **121**, 395–396.

PETTIT, E. (1936), On the color of Crater Lake water. *Proc. Nat. Acad. Sci.*, **22**, 139–146.

POOLE, H. H. (1945), The angular distribution of submarine daylight in deep water. *Sci. Proc., Roy. Dublin Soc.*, 24, 29–42.

WATERMAN, T. H. (1950), A light polarization analyzer in the compound eye of Limulus. *Science*, **111**, 252–254.

WATERMAN, T. H. (1954 A), Polarization patterns in submarine illumination. *Science*, **120**, 927–932.

WATERMAN, T. H. (1954 B), Polarized light and the angle of stimulus incidence in the compound eye of Limulus. *Proc. Nat. Acad. Sci.*, **40**, 258–262.

WHITNEY, L. V. (1941), The angular distribution of characteristic diffuse light in natural waters. *J. Mar. Res.*, **4**, 122–131.