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INFLUENCE OF GREAT INTERNAL WAVES ON THE DEPOSITION OF ORGANIC REMAINS

(3 Figs.)

Osadzanie szczątków organicznych a wielkie fale wewnętrzne

(3 fig.)

Abstract: Great internal waves may cause mass mortality of some organisms, precipitate the deposition of organic remains floating under water, and form swash marks composed of organic remains.

INTRODUCTION

The object of this paper is to present the possible significance of great internal waves for the deposition of organic remains. As far as the author knows, this has never been dealt with in a general way. The only pertinent papers that the author knows about are by Gilbert and Allen (1943) relating to standing internal waves the distribution of the phytoplankton communities in the Gulf of California in 1939 and 1940, and by Brongersma-Sanders (1957) explaining by internal waves the mass mortalities of deep living animals in the Straits of Messina in 1878 and several times since.

OBSERVATIONS OF GREAT INTERNAL WAVES IN THE RECENT SEAS AND LAKES

As implied by theoretical considerations and verified by observations, the internal waves attain their maximum amplitude in the zone of maximum density gradient. The horizontal velocities of great internal waves are usually very low. The direction of propagation of the internal waves may be different from that of the external waves. Thus e.g. in 1968 in the North Sea the internal tide traveled northward while the external tide traveled southward (Schott, 1971).

The following examples of great internal waves, taken from papers by Munk (1941), Defant (1960), Hutchinson (1966), and Ziegenbein (1969) will be given in order to show the extent of the phenomenon:

[1] Kraków, ul. Gontyna 11.

Equatorial Atlantic, 1927. Internal wave, maximum vertical amplitude 3.6 m at a depth of 100 m, period ca. 12,3 hours. It was generated by another internal wave with a maximum vertical displacement of 60 m at a depth of 100 m, with a period of 6.4 hours and a length of ca. 40 km.

North Atlantic, 1938. Internal wave, maximum vertical displacement almost 40 m at a depth of 100 m, period ca. 12 hours.

Eastern Pacific, 1930. Internal wave, maximum vertical displacement 63 m at a depth of 250 m, period ca. 24 hours.

Straits of Gibraltar, 1928. Internal breaker at depths from 50 to 275 m, maximum vertical displacement ca. 100 m; the breaker lasted for about 2 hours.

Same area, 1967. Internal waves, maximum vertical displacement 86 m, at depths from 30 to 150 m, period 11 to 13 minutes.

Gulf of California, 1939. Superposition of two internal waves resulted in an internal standing wave with maximum vertical displacement of ca. 200 m, at depths from 300 to 600 m; the length was 1000 km, the period, 7 days.

Internal uninodal seiche in one of the Pomeranian lakes in 1909 had a maximum vertical amplitude of 6 m at a depth of 15 m, the period was 25 hours.

Internal seiches in the Lake Baikal attain amplitudes of more than 150 m, the periods are up to 40 days.

It may be emphasized that no systematical world wide survey of internal waves was ever carried out. Observations of internal waves have been made mostly in shallow waters, in very few areas, and seldom longer than for a few days. The data are haphazard both in space and time. Perhaps the most important is the complete lack of data on the submarine tsunami, which probably much exceed the usual internal waves generated by other waves, currents, or tides. The only generalization from the data available that may be suggested is that the internal waves seem to attain greater amplitudes and periods in elongate channel-like bodies of deep water, such as the Gulf of California or Lake Baikal, than in the oceans. This confirms the theoretical considerations.

INFLUENCE OF GREAT INTERNAL WAVES OCCURRING HIGH OVER THE BOTTOM

If an internal wave is formed, an internal layer of water changes its position: in the crest of the wave, it moves up by half the way height, and in the trough of the wave, it moves down by the same distance. This implies a change of the hydrostatic pressure in the layer: in the crest, the pressure (in atmospheres) will diminish approximately by the vertical amplitude of the wave (in meters) divided by 10; it will augment in the trough by the same value. Furthermore, in the zone where light reaches, illumination of the layer will generally become more intense in the crest and less intense in the trough. These changes may occur over areas of several thousand square kilometers. On the other hand, the density, temperature, and salinity of the undulated layer will remain practically constant as long as the wave persits.

Usually, the great internal waves are so slow that nektonic organisms may easily escape if necessary the changing environmental factors. Only in the areas of very unstable and intricate patterns of waves and connected currents escape may become impossible and mass mortality may ensue. This happens to fishes in the Straits of Messina if the explanation of Brongersma-Sanders (1957) based on Defant's (1940) description of the internal waves is valid.

It is doubtful whether the currents were strong enough to carry the fishes which tried to escape. Rather, it seems that the fishes tended to follow an upward moving body of water of a character that attracted them in spite of diminishing pressure until it was too late for them to escape. In an analogous way, some fishes will swim up a polluted river becoming weaker all the time until they die. An additional factor may have been the disturbance of the sounds to which the fishes are sensible. Even in the most regular internal waves, the pattern of internal sound reflexion and refraction and of the zones of different sound intensity till complete silence becomes very complicated. The effect was used in submarine warfare (Scharnow, 1961).

Theoretically, unstable internal waves should be generated by currents flowing in opposite directions at different depths in not very deep waters, particularly if the tidal effect is superposed. In fact, they were observed in the straits where such conditions occur (Defant, 1960, p. 566). It may be believed that periodical mass mortality of nekton due to great internal waves should occur mostly in the straits and adjoining areas.

It is possible to explain by this phenomenon the Rhaetian bone beds of Western Europe occurring near the straits between islands of an archipelago or emerged massifs, e.g. in the Swabian Alb situated near the „Hessische Strasse" and straits in the Vindelician land.

Much more wide spread should be the influence of the great internal waves on those planktonic organisms which move slowly if at all and breed fast. Standing internal waves in a mediterranean body of water repeatedly distributed in the same pattern will determine the horizontal extension of plankton communities. The rate of breeding of the plankton is high compared to the period of the waves, and thus the communities have enough time to establish themselves. This apparently happens in the phytoplankton in the Gulf of California (Gilbert and Allen, 1934). Analogous phenomena may have occurred in the past, particularly in the elongate flysch basins bordered by cordilleras.

In the open seas, where the periods of great internal waves are commonly shorter than in the mediterranean waters, plankton communities have less time to establish themselves. The zooplankton, whose diurnal vertical migrations may exceed 500 m, may be able to escape the changed conditions if necessary. On the other hand, the very slowly moving or passively floating phytoplankton may not. It would seem that it would be little affected by the changes of pressure. However, the change of illumination may be important. The individuals brought down to less intense light in the troughs of the waves would not suffer much. Living diatoms have been found as deep as 300 m; these were forms normally occurring near the surface. The individuals brought up to more intense light would perish if the illumination were strong enough. In the diatoms, excessive illumination causes clustering of chromatophores and an increase in specific weight (Moore, 1958, p. 52, 153). Thus some species cannot persist above 10 or 20 m, depending on the transparency of water, in full sunlight. Most other algae are also injured or killed by strong light. Therefore it would seem that an internal wave of even a low amplitude of a few meters but of great length may cause depletion in phytoplankton over areas of several thousand square kilometers. This may be one of the causes of the productivity of the Recent seas being generally lower at the low, than at the high, latitudes: the internal waves at the former result in greater changes of illumination than in the latter.

Another effect would concern the floating remains of dead organisms. Upon death, bodies of cephalopods float upwards, and, if the animals died in not very deep waters, may reach the surface. Soft parts of cephalopods in the North Sea may drift for as long as four days before they decompose (S c h ä f e r, 1962, p. 192). A floating empty shell of a Nautilus was found to have sunk but very slightly after more than a month in an experiment by R e y m e n t (1958). When the shell becomes waterlogged, the remains sink till they reach denser water whose specific weight is equal to their mean specific weight, and drift there (R e y m e n t op. cit.). In an experiment by G e i s l e r (1939) a damaged shell of a Recent Nautilus floated for 28 days.

The depth at which a cephalopod shell would become crushed by the pressure of water if the pressure of gas in the shell were not raised depends on the shape, structure, and size of the shell. The internal pressure of gas in the shell of a specimen of Nautilus caught alive at a depth of 180 m was about 1 atm., and so was the pressure in a specimen caught just below the surface (S t e n z e l, 1964, p. K91). Experiments showed that shells of Spirula are crushed by pressure such as at a depth of about 2000 m (A r k e l l 1957, p. L120). It is estimated that ammonite shells would become crushed at about 1000 m; resistance to pressure seems to diminish with increasing size (l.c.).

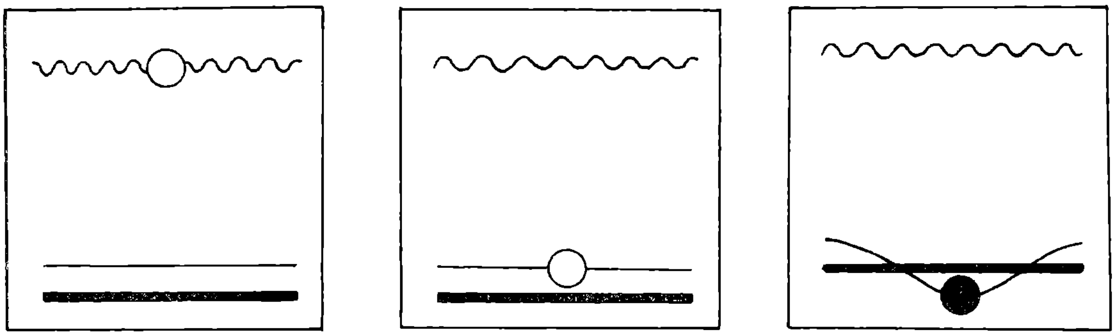


Fig. 1. Implosion of organic remains in the trough of an internal wave. Left: shell floating at the free surface; middle: waterlogged shell sank and floats at the upper boundary of denser water marked by thin line; right: shell brought down in the trough of an internal wave below the depth of critical pressure marked by thick line is being crushed

Fig. 1. Implozja szczątków organicznych w fali wewnętrznej. Na lewo: skorupa unosząca się na wolnej powierzchni; w środku: częściowo napełniona wodą skorupa pogrążyła się i unosi się na górnej powierzchni gęstszej wody oznaczonej cienką linią; na prawo: skorupa przemieszczona w fali wewnętrznej poniżej głębokości krytycznego ciśnienia zaznaczonej grubą linią jest zgniatana

If, due to an internal wave, the remains floating under water were brought below the critical depth, shells would implode, and then the remains would sink right down. A wave of quite low amplitude might cause this effect if the layer where the remains floated were situated near the critical depth (Fig. 1). In this way may have been formed some concentrations of ammonite remains in deep deposits. The following example may be given.

In the radiolarites and associated rocks of the Tethyan Jurassic, ammonites are represented by aptychi, the aragonitic shells presumably being not preserved. Almost all the specimens of aptychi — more than 99.5 per cent — are single valves. This means that the valves were detached from the soft parts before being deposited: there is evidence that there were no bottom currents strong enough to scatter the valves which reached the bottom in pairs (cf. Gąsiorowski, 1970). The detaching, therefore, occurred high over the bottom while the remains still floated, and the scattering occurred during sinking, or else the valves were detached not simultaneously.

In some horizons, however, the amount of pairs of valves exceeds 30 per cent. This may be explained in the following way. The waterlogged shells still carrying the soft parts and aptychi sank to a denser water at a depth of about 1000 m, and floated there. Before the soft parts disintegrated and the aptychi were detached, an internal wave occurred. In the trough of the wave, shells were crushed by the increased pressure and sank right down reaching the bottom together with the soft parts and the undetached aptychi.

The deep water deposits where the amount of pairs of aptychi exceeds 30 per cent are, e.g., some layers of the Upper Oxfordian red radiolarites of the Branisko Series, Pieniny Klippen Zone, in Rabsztyn, SW Pieniny Mts., Carpathians, Poland, or the Upper Kimmeridgian green siliceous marls of the same series in Łysanki West of Szaflary (for description of this outcrop, vide Birkenmajer and Gąsiorowski, 1962). In both localities, the amount of pairs of aptychi seems to depend on size, there being less than 3 per cent of pairs of specimens of length smaller than 1 cm and more than 50 per cent of specimens larger than 1 cm. This would agree with the greater resistance to pressure of smaller shells.

Implosion of air bladders in the troughs of internal waves may be responsible also for some concentrations of graptolite or algal remains.

INFLUENCE OF GREAT INTERNAL WAVES REACHING THE BOTTOM

The internal waves approaching the bottom behave in much the same wave as the external waves. Internal surf was experimentally obtained by Zeilon (1934), who used waters of different density, and by the present author, who used water and kerosene. The qualitative experiments made by the present author seemed to indicate that most littoral geological processes may be duplicated at any depth by internal waves if their energy were adequate. Below, only the influence of great internal waves on the deposition of organic remains will be dealt with.

As may be seen in the review of the waves presented at the beginning of this paper, the horizontal velocities involved are mostly too low to cause preferred orientation of heavy organic remains, or influence their distribution in any other way. They are adequate, however, to displace very small tests, either directly or by the currents they induce (cf. Revelle 1939). Possibly, the amounts of Tintinnids, Globochaete or Saccocoma laterally variable in lithologically uniform horizons of the Malm and Neocomian in the Alps and the Carpathians may be explained in this way.

Another effect of great internal waves may be the formation of enormous swash marks, comparable in size to those left by the external tsunami. Internal swash marks were experimentally obtained by the present author (Fig. 2). Organic remains floating at the boundary surface or below it are carried by the advancing internal breaker up a sloping bottom, and left there when the wave retreats. The distribution of ammonite remains in some areas of submarine elevations may be explained in this way.

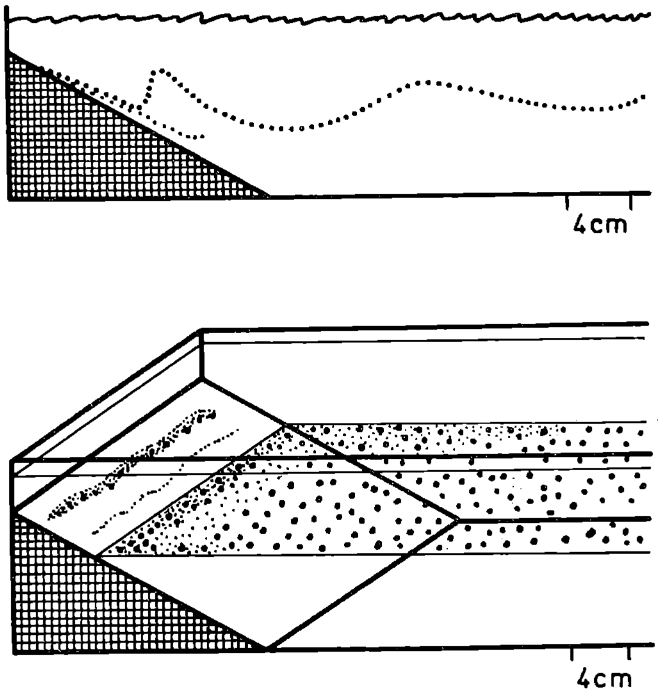
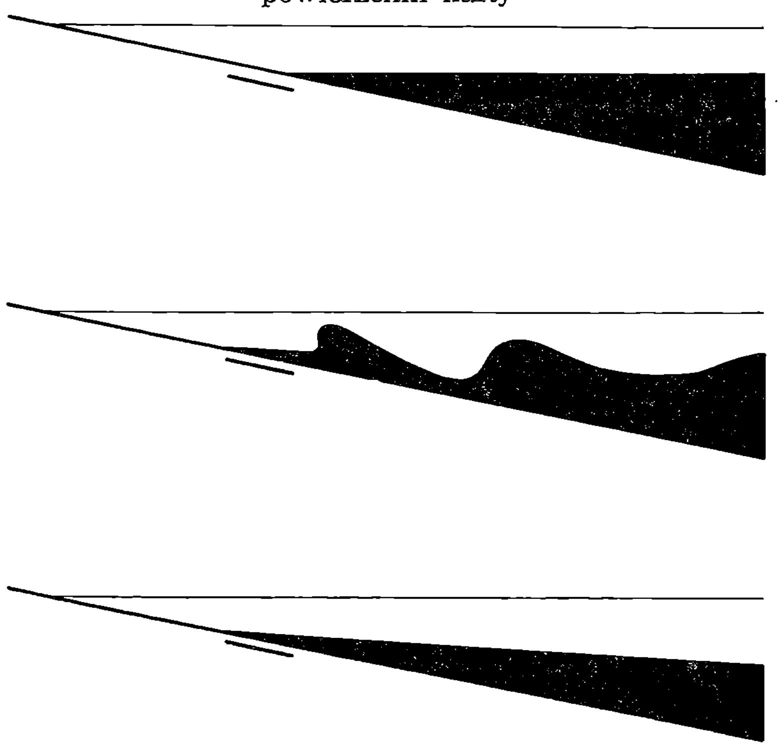


Fig. 2. Above: internal surf; below: swash marks formed by internal surf. The upper layer of fluid was kerosene, the lower layer was fresh water; objects floating at the boundary were plant detritus. Internal waves were induced by the movement of an object floating at the free surface of the kerosene

Fig. 2. U góry: kipiel wewnętrzna; u dołu: swash marks utworzone przez kipiel wewnętrzną. Górną warstwą płynu była nafta, dolną warstwą była woda słodka; przedmioty unoszące się na granicy między płynami są detrytusem roślinnym. Fale wewnętrzne zostały wzbudzone przez ruch przedmiotu unoszącego się na wolnej powierzchni nafty



If the advancing internal breaker consisted of a brine forming lower layers of water (cf. Schmalz, 1969), such as in some areas of the Recent Red Sea, benthonic organisms in the internal surf zone (Fig. 3) would be influenced. A great internal breaker may last several hours, and this may be long enough to kill some organisms. The tolerance to hypersalinity seems to be a specific or even subspecific character; too few data were published to allow a more exact statement. However, inundation by an internal seiche lasting several days would certainly be lethal for most organisms. Concentrations of remains of benthonic organisms in some horizons of the Zechstein may be due to catastrophic mass mortality episodically caused by internal hypersaline surf or seiches.

In all the basins with stratified water, a lunar rhythm may exist in the benthonic organisms living in the internal tides zones. This rhythm would be analogous to that observed in numerous shallow living organisms discussed by Korringa (1957). Therefore, rhythmical distribution of growth layers in invertebrate shells should not be considered by itself evidence of life at any depth or in any climatic conditions.

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Fig. 3. Cross section of a basin with water of normal salinity underlain by brine. Above: boundary surface at rest. Below: boundary surface undulated due either to internal waves or to an internal seiche, brine inundating part of bottom hitherto covered by water of normal salinity. Zone of inundation underlined.

Fig. 3. Przekrój basenu wypełnionego wodą o normalnym zasoleniu unoszącą się na solance. U góry: powierzchnia graniczna w spoczynku. U dołu: powierzchnia graniczna zaburzona w wewnętrznych falach lub seiche, solanka zalewa część dna poprzednio pokrytego wodą o normalnym zasoleniu. Strefa zalana podkreślona

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STRESZCZENIE

W morzach i jeziorach obserwowano fale wewnętrzne, których okresy wynosiły wiele dni, wysokość przekraczała 200 m, a długość sięgała 1000 km. Nie są znane wymiary wewnętrznych tsunami. Stwierdzono doświadczalnie (Zeilon, 1934, i fig. 2 obecnej pracy), że fale wewnętrzne zbliżając się do dna odkształcają się podobnie jak fale zewnętrzne, mianowicie załamują się, powstają podwodne grzywacze i wytwarza się strefa podwodnej kipieli. Doświadczenia wykonane przez autora wskazują, że większość zjawisk geologicznych zachodzących w strefie litoralnej może się powtarzać na dowolnej głębokości w strefie kipieli fal wewnętrznych, jeśli ich energia jest wystarczająca.

W warstwie wody przemieszczonej w fali wewnętrznej nie zmienia się gęstość, temperatura, zawartość soli i zawiesin, lecz zmienia się ciśnienie hydrostatyczne, w płytszych strefach także naświetlenie. Zmiany te mogą zachodzić na obszarze wielu tysięcy kilometrów kwadratowych i trwać wiele dni. W wodach śródziemnych często powstają stojące fale wewnętrzne, których układ się powtarza, co określa rozmieszczenie zespołów organizmów planktonicznych. Dzieje się tak obecnie w Zatoce Kalifornijskiej (Gilbert i Allen, 1943), a prawdopodobnie działo się we wszystkich wydłużonych głębokich basenach, np. w basenach fliszowych Karpat. W wodach otwartych okresy fal wewnętrznych są zwykle znacznie krótsze. Plankton roślinny w grzbietach fal może zostać zabity przez nadmierne naświetlenie. Wielkie fale wewnętrzne są zwykle zbyt powolne, aby organizmy nektoniczne nie mogły uciec przed zmieniającymi się warunkami. Tylko w bardzo niestatecznych układach fal wewnętrznych, wywoływanych w cieśninach przez prądy przeciwnie skierowane na różnych głębokościach i przez przypływ, nekton może ginąć masowo. Prawdopodobnie dzieje się tak obecnie w Cieśninie Messyńskiej (Brongersma--Sanders, 1957). Jest możliwe, że brekcje kostne występujące w strefach położonych blisko cieśnin, np. retyku szwabskiego, powstały w ten sposób.

Skorupy głowonogów częściowo napełnione wodą dryfują nie na powierzchni, ale w głębszych i gęstszych warstwach wody (R e y m e n t, 1958). Jeśli taka warstwa zostanie przemieszczona w wielkiej fali wewnętrznej, to zwiększone ciśnienie może zgnieść skorupy (fig. 1), które wtedy opadną wprost na dno. Taka może być przyczyna lokalnych nagromadzeń szczątków głowonogów w głębokowodnych osadach, np. w radiolarytach jury alpejskiej. Zgniecenie pęcherzy powietrznych glonów i graptolitów może być przyczyną niektórych nagromadzeń ich szczątków.

Wielkie wewnętrzne grzywacze mogą tworzyć olbrzymie swash marks złożone ze szczątków organicznych. Autor otrzymał doświadczalnie podwodne swash marks (fig. 2). W basenach o warstwowanej wodzie może wystąpić u organizmów dennych w strefie przypływów wewnętrznych rytm księżycowy, podobnie jak u organizmów w strefie litoralnej. Tak więc rytmiczne następstwa warstw przyrostowych skorup bezkręgowców nie muszą wcale świadczyć o życiu w płytkiej wodzie. W basenach, gdzie niższe warstwy wody są solanką, jak obecnie w pewnych częściach Morza Czerwonego, a w przeszłości prawdopodobnie np. w morzu cechsztyńskim, kipiel lub seiche na granicy wody o normalnym zasoleniu i solanki może zalać wyżej położone części dna (fig. 3). Organizmy denne żyjące na zalanym obszarze zostaną zabite, jeśli zalew trwał wystarczająco długo. Jest możliwe, że niektóre nagromadzenia szczątków organicznych w cechsztynie powstały w ten sposób.

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