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POSSIBLE SIGNIFICANCE OF INTERNAL WAVES FOR UNDERWATER EROSION

(7 Figs.)

Fale wewnętrzne a erozja podwodna

(7 *fig.*)

Abstract. It seems possible that some types of internal waves may erode significantly. In the qualitative experiments made, underwater cliffs, terraces, and backwash channels were formed in the internal surf zone.

INTRODUCTION

Internal surf may be formed if the internal waves approach the bottom. Qualitative experiments presented below suggest that the internal surf may erode in a similar way as the external surf does. Thus it would seem possible that erosional processes analogous to those in the littoral zone may occur in the zones of internal surf.

Internal surf may develop at any depth. It depends on the density stratification of water, on the morphology of the bottom, and on the factors generating internal waves.

Erosion by internal surf has not been hitherto directly observed. However, few observations of internal waves are available, and the physical theory of the phenomenon remains much better known than its natural occurrences.

Some erosional phenomena have been already tentatively referred to direct or indirect action of internal waves: lack of deposition on seamounts and other elevated areas (cf. Shepard, 1973), stirring up of sediments in deep waters off California (Emery, 1956); and Shepard and Dill (1966, p. 331) considered the possibility that valleys are excavated due jointly to reversed density stratification of water, internal tides and waves.

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THEORY

The latest theoretical studies of the deformation of the internal waves approaching the bottom are by Wunsch (1968, 1969, 1971), Larsen (1969), Robinson (1969), Sandstrom (1969), and Hasselmann (1970); see also Phillips (1966). The conclusion relevant to the present subject is that "either very rapid dissipation through friction or breaking probably takes place" (Wunsch, 1968, p. 258). The intuitive reasons may be seen in Fig. 1.

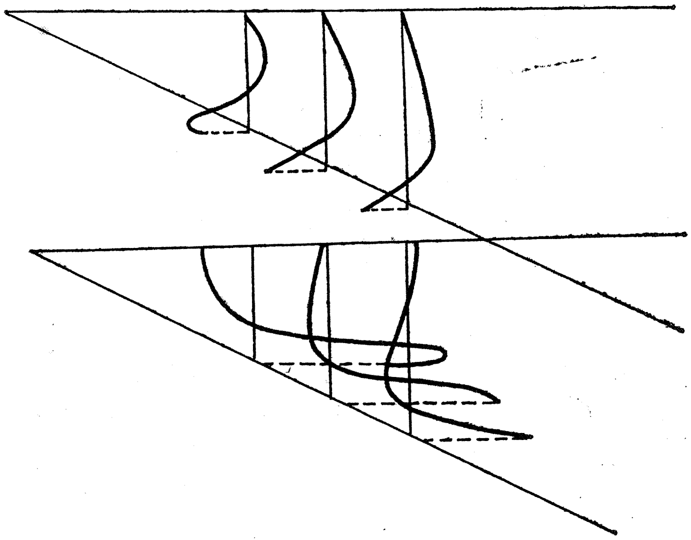


Fig. 1. Vertical (top) and horizontal (bottom) velocities of some internal waves approaching the bottom. After Wunsch 1968, Fig. 5

Fig. 1. Pionowe (u góry) i poziome (u dołu) szybkości fal wewnętrznych zbliżających się do dna. Według Wunscha 1968, Fig. 5

OBSERVATIONAL EVIDENCE

Internal breakers were observed high over the bottom e.g. in the Straits of Gibraltar (Jacobsen and Thomsen, 1934; Defant, 1934; 1960). The height was up to 200 m. The breakers formed slowly and degenerated quickly (Fig. 2). Internal breakers high over the bottom seem to develop during seiches in some lakes (cf. e.g. Mortimer, 1952). According to Haurwitz, Stommel and Munk (1959) and Wunsch (1968) the internal waves propagating upslope off the Bermudas become distorted. Shepard and Dill (1966), Shepard (1973), and Shepard and Marshall (1973) thought that the rapidly alternating bottom currents in the canyons off California may involve internal waves. LaFond (1961) found that the greatest horizonal velocities of some internal waves off California were near the bottom.

Symmetrical ripplemarks found at great depths in some areas, e.g. at 1704 fathoms off the Mississippi delta (Ter-Chien Huang and Goodell 1970), imply that the internal waves do occur just over the bottom.

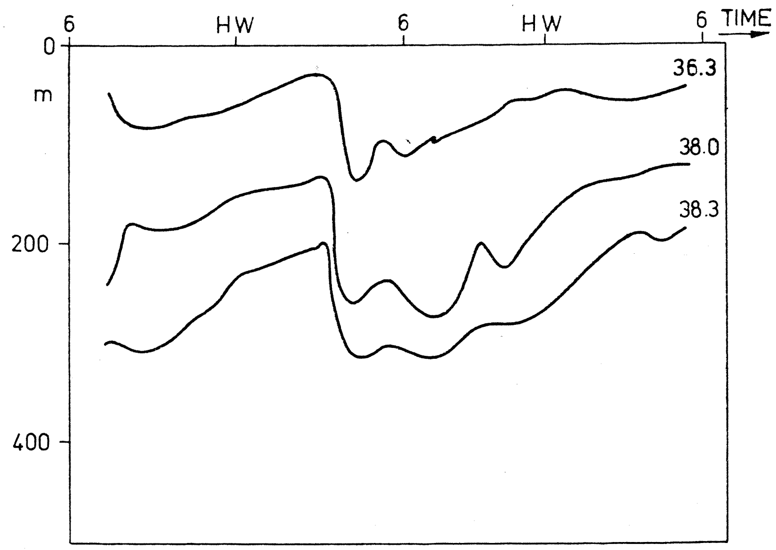


Fig. 2. Internal breaker in the Straits of Gibraltar. Numbers indicate salinity. After Jacobsen and Thomsen 1934, simplified

Fig. 2. Wewnętrzny grzywacz w Cieśninie Gibraltarskiej. Liczby oznaczają zasolenie. Według Jacobsena i Thomsena 1934, uproszczone

EXPERIMENTAL EVIDENCE

Internal surf was obtained in experiments by Defant (1929), Zeilon (1934), and others (cf. Turner 1973).

In the qualitative experiments made we tried to obtain cliffs and terraces formed by internal surf, and channels excavated by the associated backwash currents.

The eroded material was wood, preferably oak, sawdust soaked in water for a few days.

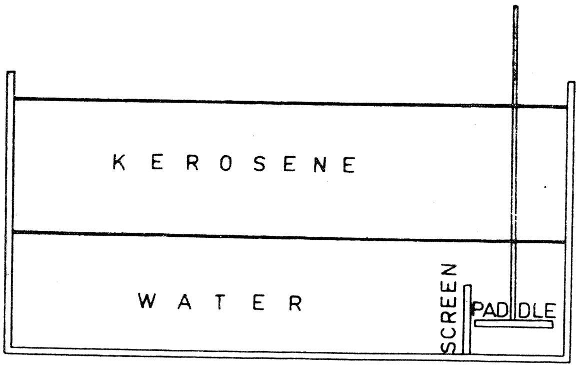
Two sets of fluids were used:

(1) Saline and fresh water. Bits of ice were put on saline water coloured with ink. When the ice melted, a two-layer system was obtained. This set proved impractical as the waters mixed very easily due to the great energy of the waves in relation to the dimensions of the water layers. Moreover, the set could have been used only once, as re-shaping of the eroded material resulted always in complete mixing of waters.

(2) Water and kerosene. The great advantage was that these fluids did not mix. Thus it was possible to prolong indefinitely an experiment, and later to re-shape the eroded material in order to prepare it for another experiment.

It seemed that the saline and fresh water set did not imitate the natural conditions in one important respect, namely, the water layers mixed too readily. In this respect the water-kerosene set was perhaps nearer to the natural conditions.

The internal waves were induced by a horizontal paddle moving in the lower layer (Fig. 3).



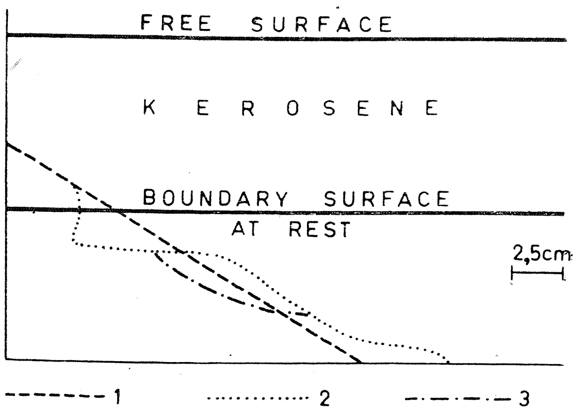


Fig. 3. Apparatus used in experiments
Fig. 3. Zbiornik używany w doświadczeniach

Fig. 4. Profile of cliff, terrace and backwash channel eroded in wood sawdust by internal waves. Sediment profile 1 — before; 2 — after experiment; 3 — backwash channel

Fig. 4. Profil klifu, terasy i kanału wyerodowanych przez fale wewnętrzne. Profil osadu 1 — przed, 2 — po doświadczeniu; 3 — kanał spływowy

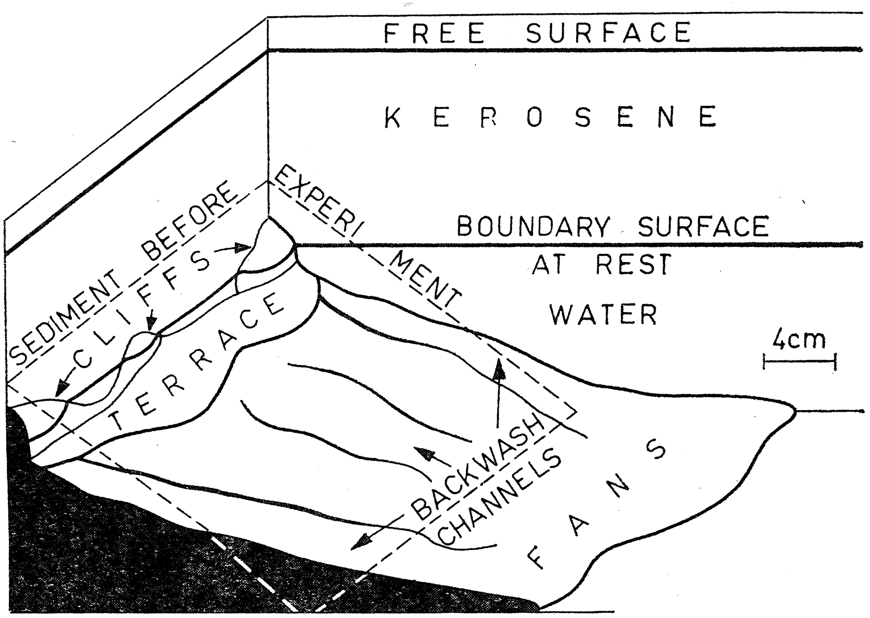


Fig. 5. Cliffs, terrace and backwash channels eroded in wood sawdust by internal waves

Fig. 5. Klif, terasa i kanały wyerodowane w trocinach przez fale wewnętrzne

The following erosional forms were obtained in the internal surf zone (Figs. 4—6):

1. Cliffs. They appeared at the beginning of the experiments and receded due alternately to undercutting and the resulting slumping. Simultaneously

2. a terrace developed. It was formed jointly by erosion in its inner part, at the feet of the receding cliffs, and by accumulation in its outer part. Sometimes a shallow and wide trough appeared in the inner part

of the terrace, at the feet of the cliffs, to disappear quickly. Generally, the terrace sloped gently away from the cliffs to its outer margin. The terrace developed below the boundary surface, about the depth where the internal waves were breaking. The outer margin of the terrace receded where

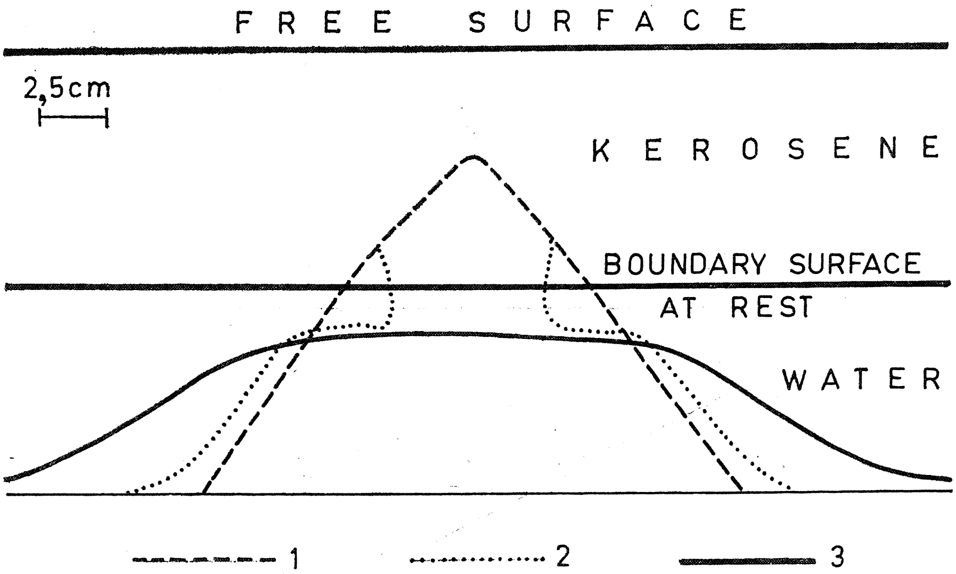


Fig. 6. Truncation of a cone of sawdust by internal waves. Sediment profile 1 — before, 2 — during, 3 — after experiment

Fig. 6. Ścięcie stożka usypanego z trocin przez fale wewnętrzne. Profil osadu 1 — przed, 2 — podczas, 3 — po doświadczeniu

3. backwash channels developed. They were beginning just at the outer margin of the terrace and continued downslope to the area where the fans formed; in the later stages of the experiments they cut across the upper parts of the fans.

DIFFERENCES BETWEEN INTERNAL AND EXTERNAL SURF EROSIN

The dimensions of the internal waves commonly exceed those of the external waves. Internal waves with an amplitude of tens of meters are not at all uncommon. Therefore, the zone of possible erosion by internal surf may be much wider than that by the external surf.

The volume of water carried up by an internal breaker being greater, the backwash should be more important and the excavated forms, if any, larger than in the case of external waves.

Water and air, though partly miscible, retain their characters of fluid and gas. Therefore the external surf may persist unchanged indefinitely. Waters of different density are wholly miscible, and therefore turbulence associated with surf will result in the density gradient in the internal surf zone becoming less and less steep (Fig. 7). This will determine a change in the character of the waves: each incoming internal breaker will be different from the preceding ones.

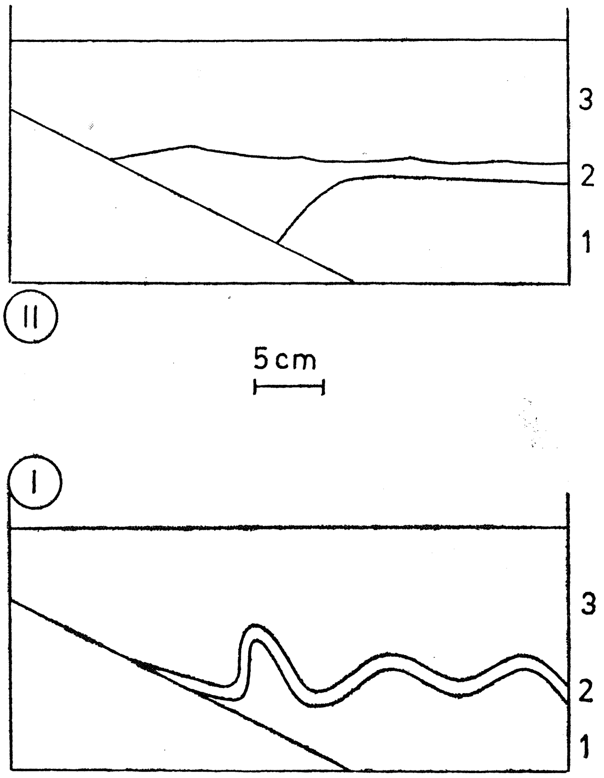


Fig. 7. Mixing of waters in the internal surf zone
Fig. 7. Mieszanie się wód w strefie kipieli wewnętrznej

It seems that there are fewer possible factors determining the external than the internal surf. Thus the internal surf appears to be a more complex phenomenon. It is therefore possible that forms due to internal surf erosion are less regular.

FACTORS DETERMINING THE INTERNAL WAVES EROSION

Stratification of Water

The boundary (distinguished from cellular and other types) internal waves attain greatest dimensions in the zones of high density gradient.

The density depends on temperature, salinity, and depth, as "two waters that differ in potential temperature and salinity, but have the same density at particular pressure, will not have equal density at any other pressure" (Weyl, 1969, p. 513).

The stratification of water bodies depends on several factors, of which the most important seem to be:

1) Differences of temperature at different latitudes. This determines the equatorward flow of cold polar waters, assuming an inclination of the axis of rotation of the Earth to the ecliptic nearer to perpendicular than to parallel.

2) Configuration of lands, shelves, and oceans. N-S oceans would

make easier a density circulation of waters, while E-W oceans would inhibit it.

3) The tides make possible a transfer of energy which may be used for mixing waters of different density. The importance of the tides may have changed considerably; it is determined by the morphology of the Earth and by astronomical factors. A review of contradictory opinions is presented by Pollard (1969).

It would seem that no reliable estimate of stratification of water bodies in the past may be made.

Energy of Internal Waves

The essential question is whether the energy of the internal waves occurring in natural conditions is adequate to erode significantly.

The Coriolis force tends to diminish the length of internal waves, to increase their height, and to shorten their periods (Krauss, 1957; Defant, 1960), thus tending to augment their energy. Therefore, the higher rate of rotation of the Earth in the past should have resulted in higher-energy internal waves. With varying estimates of the secular slowing down of the rotation it is impossible to decide whether the difference could have been significant.

The energy of the internal waves depends also on their cause. Below are presented the possible causes of the internal waves and similar movements.

1) Internal waves induced by the external waves (e. g. Phillips 1966, p. 172—72). Their dimensions exceed those of the external waves, but their velocity is very much smaller (about 45 times — Defant, 1960, p. 518), and therefore their energy is much lower.

2) Internal waves generated by changes of atmospheric pressure or gusts of wind (cf. Phillips 1966, p. 171). Observations imply that their energy is also rather low (cf. e. g. Defant, 1960, p. 526).

3) Internal tides were observed e. g. in the North Sea (Schott, 1971), any many internal waves in rather shallow layers of the open seas have tidal periods (Defant, 1960). Short-period waves may develop on internal tidal fronts (Ziegenbein, 1969). It seems that the energy of the internal tides is lower than that of the external ones, as they move more slowly.

4) Internal seiches may last for a very long time (up. to 912 hours in the Lake Baikal — Mortimer, 1953). Their energy is probably comparable to that of the external seiches.

5) Internal waves induced by currents (Phillips, 1966, p. 171). Some are quite simply lee waves, other may have a different character. Currents influence the development of internal tidal waves in the Straits of Gibraltar (Defant, 1960, p. 562). See also Phillips, George and Mied (1968).

6) Internal waves induced by turbulence associated e. g. with penetrative convection (cf. Turner, 1973, pp. 237, 335).

7) Internal waves induced by the movement of floating objects, whether artificial as ships (Ekman, 1904) and submarines, or natural as icebergs. The latter have been never observed, as far as the present author knows, but they should have been common over vast areas during glacial periods and even now. The former are evidently a recent phenomenon still of a limited extent. The energy of the internal waves thus induced depends on the size, shape, and the rate of movement of the floating object. In the case of induction by icebergs, it should probably be rather low. It is interesting whether the movement of shoals of Fish or swarms of Cephalopods is able to induce significant internal waves. If so, such waves, though intermittent, should be quite common.

8) Internal waves induced by earthquakes. As far as the present author knows, they have not been hitherto observed. It seems however probable that they occur commonly. The energy of the earthquakes being enormous, the internal tsunamis might possess energy several orders of magnitude higher than the other types of internal waves reviewed above.

FORMS POSSIBLY DUE TO INTERNAL SURF EROSION

There occur at various depths in seas and lakes forms analogous to those due to littoral erosion. These are: terraces, from the continental shelf to smaller ones cut in continental and other slopes and to flat top surfaces of the guyots; steep surfaces cutting across rock, particularly in some parts of the continental slope; deep submarine canyons and gullies in the continental slope. It is suggested that such forms might be due to erosion by internal surf and associated backwash currents.

Most of these forms differ from the littoral ones in two respects: size, being much greater; and regularity, being less regular. The latter may be apparent, due to smaller accuracy of the bottom maps.

These differences would not be inconsistent with the internal surf erosion. As pointed out previously, the dimensions of the internal breakers may commonly exceed those of the external breakers; this would account for size. The internal surf seems to be a more complex phenomenon than the external surf; this might account for the lesser regularity of effects.

It may be not a coincidence that the average depth of the continental shelf margin agrees with the position of the thermocline. The average depth of the shelf margin is 130 m (Shepard, 1973, p. 277). The thermocline, in an equatorial zone about 60° wide is situated generally between 100 and 200 m, and at high latitudes the lower boundary of the cold intermediate layer during warm seasons is commonly between 60 and 150 m (Defant, 1961). It is also perhaps significant that some shelf margines in subtropical and tropical regions seem to become shallower roughly equatorward, the thermocline rising in the same directions. This is visible e. g. along the western coasts of Africa, excepted near the mouth of the Congo, where the shelf margin becomes deeper.

From Menard's (1964) data one might probably conclude that the average depth of the shelf break in Pacific guyots varies with latitude, diminishing south of about 30° S and north of about 30° N. This might suggest a connection with a boundary of waters of polar origin in the past.

CONCLUSION

It seems that it cannot be excluded that the internal waves are a significant factor in underwater erosion. In any case, they would provide a simple explanation of some common underwater forms.

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STRESZCZENIE

Rozważania teoretyczne i doświadczenia wskazują, że niektóre fale wewnętrzne zbliżając się do dna odkształcają się podobnie jak fale zewnętrzne. Wytwarza się strefa wewnętrznej kipieli. Można przypuszczać, że w strefie tej może zachodzić erozja analogiczna do lioralnej. Różnice byłyby następujące: 1) Fale wewnętrzne są często znacznie większe od zewnętrznych — amplitudy kilkudziesięciometrowe występują pospolicie — i dlatego strefa kipieli wewnętrznej może być znacznie szersza. 2) Ponieważ masa wody unoszonej w grzywaczu wewnętrznym może być znacznie większa, więc i masa wody odpływającej z plaży wewnętrznej będzie odpowiednio większa, i wyżłobione formy mogą mieć większe wymiary. 3) Woda i powietrze, choć się częściowo mieszają, zachowują cechy cieczy i gazu, i dlatego kipiel zewnętrzna może trwać bez zmian przez nieograniczony czas. Natomiast dwie wody o różnej gęstości mogą się wymieszać całkowicie. Turbulencja w strefie kipieli wewnętrznej winna prowadzić do mieszania wód, co pociągnie za sobą stopniową zmianę charakteru kipieli: graniczne fale wewnętrzne zostaną zastąpione przez inne typy. 4) Kipiel wewnętrzna jest zjawiskiem znacznie bardziej skompli-

kowanym od zewnętrznej, dlatego formy przez nią utworzone mogłyby być mniej regularne od litoralnych.

W jakościowych doświadczeniach przeprowadzonych obecnie otrzymano następujące podwodne formy erozyjne utworzone przez kipiel wewnętrzną: klify; terasy; kanały wyżłobione przez wodę odpływającą z plaży wewnętrznej (fig. 3—6).

W warunkach naturalnych erozyjna działalność fal wewnętrznych nie była nigdy jeszcze bezpośrednio obserwowana. Obserwacje fal wewnętrznych są żmudne i wykonano ich dotąd niewiele. Opisywano jednak podwodne grzywacze (np. w Cieśninie Gibraltarskiej, wysokość około 200 m — fig. 2), a obecność symetrycznych ripplemarków na dużych głębokościach świadczy, że mogą występować tam blisko dna fale wewnętrzne.

Erozją przez fale wewnętrzne można by tłumaczyć wiele form podwodnych: różne terasy, od szelfu kontynentalnego do mniejszych terasów w różnych zboczach i do płaskich powierzchni guyotów, kaniony i inne doliny podwodne.

Zasadniczą sprawą jest, czy energia występujących w naturze fal wewnętrznych jest wystarczająca. Energia fal wewnętrznych zależy między innymi od siły Coriolisa i od pochodzenia samych fal.

Obrót Ziemi dokoła jej osi staje się stopniowo wolniejszy, siła Coriolisa była więc dawniej większa niż obecnie. Nie wiadomo jednak, czy różnica ta była na tyle duża, aby mogła mieć jakiekolwiek znaczenie.

Fale wewnętrzne mogą być wywołane przez różne przyczyny: fale zewnętrzne; wiatry i różnice ciśnienia atmosferycznego; przypływy; seiche; prądy; ruch pływających przedmiotów, np. gór lodowych; trzęsienia ziemi. Największą energię mają prawdopodobnie wewnętrzne tsunami, a następnie fale wywołane przez prądy i wewnętrzne przypływy, i seiches. Czy ta energia jest wystarczająca do erozji na większą skalę, nie wiadomo z braku obserwacji. Energia pozostałych typów fal wewnętrznych wydaje się nieznaczna.

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