Possible Types of Coastal Evolution Associated with the Expected Rise of the World’s Sea Level Caused by the “Greenhouse Effect”

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Abstract

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The determination of possible coastal depositional evolutionary types under conditions of a predicted sea-level rise caused by the “greenhouse effect” can be based on the study of the data of the irregular Holocene transgression.

In general, different rates of sea-level rise cause dissimilar intensities of erosional processes, various rates of fluvial sediment discharge, dissimilar intensities of the rearrangement of the bottom profile, and thus differences in the coastal sediment budget.

On shallow-water sea coasts, there are three types of coastal evolution dependent on rate of sea-level rise and sediment availability: (1) the inundation and preservation of the depositional form; (2) displacement of the depositional form accompanied by retreat of its margin; and (3) long-term continuous shoreline progradation.

On the deep-sea coast, two types of depositional evolutionary forms occur: (1) interrupted accretion and the tendency to erosion and to reduction of the dimensions of the form; and (2) continuous sediment accretion and the tendency to increase the dimensions of the form.

Additional Index Words: Sea-level rise, sedimentation, coastal change.

Introduction

The questions associated with coastal evolution under conditions of sea-level rise have great importance at the present time because of the “greenhouse effect” problem, the forecast of appreciable warming of the climate because of the accumulation of carbon dioxide and other industrial products of combustion in the earth’s atmosphere. This warming is expected to cause a melting of existing glacial ice which will subsequently lead to a rise in the world’s sea level.

A forecast of the effects of sea-level rise on the evolution of different coastal types, especially on the depositional coasts (the most important for human activity), can be based on the existing data regarding the evolution of the world’s shoreline during the Holocene transgression. Much information can be derived from the specific characteristics of the Azov-Black Sea basin, see the initial detailed descriptions by Nefesky (1958, 1959, 1960, 1961).

In general, the conditions associated with sea-level rise contribute to a manifestation of shore erosion, the retreat of the shoreline and the landward displacement of the entire beach profile that is well known from the early works of Gilbert (1885) and Johnson (1919). Later efforts include those of Zenovich (1955, 1957, 1962), Ionin (1955), Fischer (1961), Bruun (1962), Schwartz (1967), Sanders and Kumar (1975), and Swift and Moslow (1982) along with Dolotov et al. (1964) and Dolotov (1971). Coastal flooding leads to an acceleration of the entire range of shore erosional processes, to the formation of active cliffs and to other erosional relief forms. The erosional responses may differ considerably because of stability of the rock formations relative to the processes of cliff recession and because of the character of the features found at the base of the cliff.

In the literature there is a widely-held opinion that under conditions of sea-level rise, a shoreline composed of unconsolidated sediment and with an equilibrium profile will develop in accordance with the “Bruun Rule” (Bruun, 1962; Schwartz, 1967). According to the Bruun Rule, the sediment erodes in the upper part of the beach profile and accretion occurs on the lower part of the sub-
Figure 1. Relief-forming and depositional processes on the shallow coast under conditions of sea-level rise: (a) transgression and burial by finer sediment; (b) displacement of the depositions form, accompanied by erosion on its seaward margin; (c) long-term and continuous shoreline progradation; 1, 2, 3 the positions of sea-level and resulting profile in the course of three stages of successive sea-level rise.

SHALLOW-WATER SEA COASTS

It has been presented (Dolotov, 1962, 1971, 1989) that under conditions of sea-level rise on shallow-water depositional coasts, there are three possible types of shoreline evolution.

The Inundation and Preservation of Depositional Forms

In the course of rapid flooding of the coast, the rearrangement of the profile by adaptation of the hydrodynamic factors to the conditions of depth changes (thereby insuring the possibility of sediment movement landward on gently-inclined bottom profiles) “lags behind” in comparison with the flooding of the land. As a result, the volume of sediment supplied to the upper part of the submarine shore slope is not sufficient to insure the progradation of the shoreline. Sediment that might be supplied to the shoreline by erosion of cliffs is very limited because accelerated cliff erosion can only occur in easily eroded formations because of the very short time of exposure of cliffs to the erosive action of waves (Dolotov, 1989). The rapid sea-level rise causes an elevation of the base level of the streams leading to the sea and that in turn leads to the reduction of the current velocity and the quantity of transported sediment that enters the estuaries and eventually contributes to the depositional coastal landforms.

In the case of shallow-water sea coasts, the inundation (accompanied by some initial erosion of the surface) and the subsequent burying (preservation) of existing depositional forms (Figure 1a) on the seaward portion of the profile, lower than the fair-weather wave base position, are typical (Dolotov, 1962, 1971). Forms such as barriers are often created in the zone of intensive wave action. They are capped by deep-sea fine sediment. The formation of these features corresponds to the case of “in place drowning” as ident-
tified by Gilbert (1885) toward the end of the past century and to the situation recently presented by Busch (1974) under conditions when the rate of sediment supply is lower than the rate of relative submergence caused by sea-level rise.

The incorporation of coarser sedimentary layers within muddy units of Holocene age has apparently been caused by a similar developmental situation and has been noticed by many researchers in many different areas: in the Sea of Azov (Leontiev and Leontiev, 1956; Dolotov, 1962), the Black Sea (Nevesvky, 1958, 1959, 1960, 1961), the Gulf of Mexico (Fisk, 1959), the Bering Sea (Shcherbakov, 1961), the Sea of Japan (Medvedev et al., 1961), the Sea of Okhotsk (Vladimirov, 1959), the Mediterranean Sea (van Straaten, 1959), and on the U.S.A. Atlantic coast (Kumar and Sanders, 1976). As sea level rises, the barrier remains in place as the adjoining bay deepens and widens landward. Afterward, the shoreline retreats in stepwise fashion to another landward location as a product of the inundation, as described by Gilbert (1885).

Displacement of Depositional Form Accompanied by Erosion of Its Seaward Margin

The second possible shoreline type that can occur on shallow-water depositional coasts is associated with appreciable erosion of the depositional forms and displacement of these forms with flooding (Figure 1b). This situation would take place under three conditions: (1) sufficiently rapid sea-level rise, (2) a slow rate of displacement, and (3) a total exhaustion of the sediment supply (Dolotov, 1989).

Under conditions of sufficiently rapid sea-level rise, the major relief-forming process is the coastal flooding and erosional processes that are greater than the rate of landward transfers of sediment. This situation occurs despite the greater intensity of the erosional processes on the adjoining cliff because of the longer time of wave-action on the same sea level position compared to the previous type. For this reason, the volume of sediment supplied by cliff erosion to the seaward margin of the subaerial depositional form and accumulated there can be less than the volume under the previously eroded condition of land inundation (Dolotov, 1971). Such a situation has been ascribed, for example, for the Holocene geomorphologic history of the coasts of the Bering Sea (Ioinin, 1955) and the Sea of Okhotsk (Vladimirov, 1958).

Displacement of depositional forms at the shoreline such as spits which are adjacent to erosional coastal areas is caused by the accelerated retreat of the cliffs which brings the adjoining depositional forms inland with them (Zenkovich, 1946). An example of this association is on the northern coast of the Sea of Azov. The evidence consists of the narrowing of the spits in their middle sections, the truncation of the older beach ridges by the eroding recent shoreline, partial erosion of the lagoonal muddy sedimentary strata, and the existence of ancient beach sediments for a great distance from the modern shoreline and the presence of this sediment blanket in a seaward-thinning wedge (Dolotov, 1962). The rate of the displacement of the external margin of the spit depends on the amount of the sediments being supplied from the erosion of the adjacent cliff. And that, in turn, is related to the composition of the rock formations, the height of the cliffs, the length of the erosional shoreline, and by the wave-intensity (Dolotov, 1989).

Under conditions of sufficiently rapid sea-level rise, such displacement occurs at the depositional barriers that are not directly associated with the changes in their adjacent clifffed coasts. For example, such an evolution of barrier islands has been characterized for the separate stages of the geologic history of the coast of the Sea of Azov (Dolotov, 1962) and the Caspian Sea (Dolotov, 1958), as well as on the U.S.A. Atlantic coast (Ryer, 1977; Leatherman, 1983). Such a displacement of barrier islands evidently could take place during the initial submarine stages of their evolution (of shallow-water sand banks) as well as after their appearance above sea-level (Dolotov, 1958).

Under conditions of sufficiently rapid sea-level rise, the sediment supply is continuously increasing because of abundant marine erosion and because of a considerable sediment supply being provided by fluvial processes (under conditions of less severe coastal flooding of river mouths and estuaries than in the first evolution type). However, the amount of sediment that is supplied to the downdrift margins of depositional forms does not compensate for the volume of sediment that is transferred to the underwater component because of flooding. For this reason, the dimensions of the depositional forms during the Holocene tend to decrease and some are totally lost (Dolotov, 1971).

Because of the total increase of the sediment supply in the coastal area, the bottom surface must grow upward, but it is not appreciable be-

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cause the rapid change of the shoreline position leads to the stretching of the sediment blanket over the great extent of the profile (DOLOTOV, 1971). The existence of thin sedimentary strata in the present environment represents the former depositional features and the extensive erosion of the previous forms. They have been described in the coastal zone of the Black Sea (NEVESSKY, 1958), and the Sea of Okhotsk and the Bering Sea (SHCHERBAKOV, 1983). The formation of the thin residual sand blanket accompanied by the appreciable bottom erosion (or by shoreface retreat) has been noticed on the U.S.A. Atlantic coast (SWIFT, 1976; SWIFT et al.; 1973; STUBBLEFIELD et al.; 1983). It is necessary to note that the sediment blanket often has been interrupted and that a lag cobble pavement has been observed (WALKER and THOMPSON, 1968). This type of coastal evolution can be considered to be a “discontinuous depositional transgression” type as described by CURRAY (1964).

Under conditions of a slow sea-level rise when sediment reserves are insufficient and their required replenishment from external sources is not provided, the displacement of the margins of the depositional forms landward (accompanied by erosion) is not caused by the landward retreat of the nearby cliffs. It is caused by the sediment deficiency that results from the slowing down of the shore erosion processes and therefore the reduction of the supply of sediment available for transport and deposition (DOLOTOV, 1971). The accelerating erosion of the depositional forms, such as at the basal portion of spits, sometimes leads to their transformation into detached features, as has been described for the Black Sea (ZENKOVICH, 1953).

Depositional forms can experience displacement accompanied by erosion of the margins of the forms that is not caused by the slowing down of the sea-level rise (DOLOTOV, 1971). This may be explained simply by the exhaustion of the sediment reserves in the offshore zone that occurs during the profile rearrangement and shoreward sediment movement during the sea-level change. It can take place because of insufficient replenishment of the local sediment reserves through alongshore drift. It can be an area with inadequate sediment supply in the first place. Under such conditions, the inundation is the dominant morphological process covering profile rearrangement, accompanied by transfer of some of the sediment landward.

Long-Term Continuous Shoreline Progradation

The third type of shallow-water coastal evolution (Figure 1c) is characterized by the long-term sediment accretion and the continuing seaward coastal progradation (DOLOTOV, 1989). It takes place when the volume of supplied sediment exceeds the volume of unconsolidated material that becomes flooded in the course of the sea-level rise. Such a coastal evolution type is typical during the slowing down of sea-level rise in the presence of abundant sediment reserves in the coastal area. During that time, the maximum rearrangement of the submarine shore slope occurs (DOLOTOV, 1971). It is accompanied by the most intensive sediment supply shoreward because, according to ZENKOVICH (1957), during the slower rate of sea-level rise the profile rearrangement is more intensive. LEONTIEV (1961) and NEVESSKY (1961) noticed that at these times the maximum coastline progradation is achieved. Under conditions of minor land flooding, the rearrangement causes a transfer of the sediment and for this reason, the relatively small flooded area of the depositional forms becomes less than the area that is added as a result of the sediment transfer from the sea bottom shoreward and its accretion to the subaerial component (DOLOTOV, 1971). The characteristics of this type of coastal evolution is similar to the “depositional transgression” type described by CURRAY (1964).

One of the examples of a depositional transgressive coast is on the northern coast of the Sea of Azov. Because of the slowing down of the sea-level rise, as determined in 1959 (DOLOTOV, 1962), the rate of cliff recession has become appreciably reduced. A wide beach has developed and it has built out over an entire spit, including the part attached to the cliff where beach erosion occurred earlier (accompanied by truncation of beach ridges). The same evolution type has been described for the Arabat “arrow”, a long barrier island on the Crimea Peninsula, in that time period. Seaward progradation of the barrier islands as well as increases in height and volume have also been described for the U.S.A. Atlantic coast (PSUTY, 1986).

Shore progradation is especially characteristic under conditions of a continuing supply of sediment from the large rivers because of the reduction in the rate of base level rise (DOLOTOV, 1971). In the Holocene period, it has been described for the region of the Rhone delta (VAN STRAATEN,
1959), on the Mexican coast (Curray and Moore, 1964), and on the coast of western Kamchatka (Zenkovich and Vladimirov, 1951).

Under conditions of the slowing down of the rate of sea-level rise and the availability of sediment, the barriers experience coastal progradation and an increase in height (Gilbert, 1885; Zenkovich, 1957; Dillon, 1970; Rampino and Sanders, 1980; and Leatherman, 1983). In such conditions on the western part of the Sea of Azov, Leontiev and Leontiev (1956) have shown that a chain of separate islets was transformed into a united subaerial barrier (Arabat “arrow”). The same phenomenon has been noticed on the Chuckchee Sea coast (Danilov et al., 1980).

DEEP SEA COASTS

On deep-water coasts, in general, the depositional forms that are composed of sediment derived from the erosion of cliffs due to the accelerated shore erosion processes caused by sea-level rise must receive a significant amount of sediment.

The evolutionary character of every shore depositional feature is the product of two opposing factors: (1) the rate of sea-level rise (with a tendency to flooding of the accumulation form, to the retreat of its margin landward, and to the reduction of its area), and (2) the rate of sediment availability (with a tendency to coastal progradation and to the increase of the area of the depositional form). The final result of the two opposite tendencies will determine the evolution type (Dolotov, 1989). Under conditions of rapid sea-level rise, the retreat of the seaward margin of the depositional form may be traced over its entire extent.

On the deep-sea coast under conditions of sea-level rise, the displacement of the seaward margin of the depositional form is caused mainly by the rate of cliff recession due to margin erosion (Figure 2a). For this reason, the rearrangement caused by the accelerated cliff retreat reaches its maximum extent at depositional forms which are adjacent to promontories (such as spits).

When the rate of sea-level rise is reduced, the cliff erosion usually slows down also and leads to a sediment deficiency at the seaward margin of the depositional forms and to the reduction of their area.

Under conditions of a fluvial sediment source, it is possible that the area of depositional forms at the deep-sea coast may increase as sea-level rises (Figure 2b, left). However, the reduction of the alluvial sediment delivery to the coast is usual because of river mouth flooding (Dolotov et al.; 1964). It leads to the inland retreat of the shoreline (Figure 2b, right).

CONCLUSION

In general, the most important factors that will cause the development of the different charac-
teristics of coastal evolution types during the antici-
pated worldwide sea-level rise will be: (1) the rate of sea-level rise; (2) the nature of the relief-
forming environmental dynamics (the hydrody-
namic factors); and (3) the amount of sediment
available (the reserve and the conditions for re-
plenishment).

The rate of sea-level rise determines the du-
ration and therefore the total intensity of the hy-
drodynamic processes. The nature of the envi-
ronmental dynamics determines the magnitude
(depth) of the reworking of the sedimentary strata
or the rate of its increase in thickness under the
influence of wave and currents. In the coastal ar-
eas, the volume of the mobile unconsolidated ma-
terial will dictate the manner of using the ambient
hydrodynamic energy and will lead to either the
seaward loss of sediment or the landward gain.

As shown above, sea-level rise does not always
lead to shore erosion and retreat. Therefore, the
widespread beach erosion of the present may not
be due only to the rise of sea level. Marine erosion
may often be caused by local human activity; for
example, by the artificial regulation of river run-
off, by sand mining of the beach material, and by
the building of a variety of shoreline structures.

Predictions of the rates of possible future sea-
level changes for the near term, as proposed by
Hoffman (1984) to average some centimeters per
year, are comparable to the rates of rise during
stages of the Holocene. Thus, it is suggested that
future development of the shallow-water coasts
probably should follow the second and third
coastal evolutionary types described above. Fore-
casts of the particular evolutionary model must
be based primarily on the estimates of the sedi-
ment budget in the specific area.

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RESUMO

A previsão das modificações nos ambientes sedimentares costeiros provocadas pela elevação geral do nível do mar, pode basear-se nas testemunhos da transgressão Holocênica, apesar da irregularidade desta. As consequências da elevação do nível do mar, na costa, dependem da amplitude da elevação, e também da susceptibilidade à erosão das formas do relevo litoral, e do novo balanço de sedimentos que se estabelece durante e após a dinâmica de submersão das formas baixas (de acumulação) e devido ao incremento da erosão na base das arribas, nas praias e nas dunas.

Nos litorais pouco profundos verificam-se três tipos de evolução, dependentes da amplitude da elevação do nível do mar e da disponibilidade de sedimentos: (1) submersão e preservação das formas de acumulação; (2) deslocamento das formas de acumulação acompanhado pelo recuo das respectivas margens; (3) progressão contínua da linha de costa, a longo termo.

Nos litorais profundos verificam-se dois tipos de evolução das formas de acumulação: (1) interrupção na acumulação, tendência para erosão e consequente redução do tamanho dessas formas; (2) deposição contínua dos sedimentos e tendência para um maior desenvolvimento das formas de acumulação. Discutem-se as várias possibilidades de evolução da costa consoante a inclinação e a extensão da plataforma litoral, a rápida ou lenta elevação do nível do mar e a disponibilidade de sedimentos na costa setentrional do Mar de Azov.
RÉSUMÉ

La prévision des conséquences de l’élévation du niveau de la mer sur la sédimentation littorale peut se faire en analysant les témoins de la transgression holocène, en dépit de son irrégularité.

Ces conséquences dépendent de l’amplitude et de la vitesse de la remontée du niveau de la mer, de la résistance des roches à l’érosion marine et du nouveau bilan sédimentaire littoral, qui s’installe pendant et après la dynamique de submersion des formes basses (surtout celles d’accumulation), à cause de l’érosion qui est accélérée sur les plages, sur les dunes et sur le bas des failles en roches tendres.

Sur les littoraux peu profonds on observe trois types d’évolution: (1) submersion et préservation des formes d’accumulation; (2) déplacement et recul des formes d’accumulation; (3) progression, à la longue, de la ligne de rivage.

Sur les littoraux profonds deux types d’évolution sont considérés: (1) interruption de l’accumulation et érosion des formes; (2) déposition continue de sédiments et engraissement des formes d’accumulation.

Dans cet article sont aussi exposées les diverses possibilités de changement de la ligne de côte en conséquence des remontées lentes au rapides du niveau de la mer, sur des côtes à large plateforme littorale et sous différentes conditions de bilan sédimentaire. La côte nord de la Mer d’Azov est présentée comme exemple.