THALASSOSTATIC TERRACES AND PLEISTOCENE CHRONOLOGY

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I. Introduction

Rejuvenation and aggradation are among the usual adaptations of a river under changing conditions. Terraces may result from rejuvenation, and a repeated alternation of rejuvenation and aggradation may lead, but does not necessarily so, to the formation of a sequence of terraces bordering a valley. Many agencies are involved in terrace formation. The correlation of terraces along different rivers, or even along different parts of the same river, often meet with serious difficulties.

However, under certain conditions the causes involved may be of such a nature as to affect all rivers in a vast area in the same way. This has been the case for instance during the changing glacial and interglacial conditions of the Pleistocene. Their effects are well developed in the middle course of several rivers in the periglacial belt of temperate Europe. On paleontological evidence it is assumed, that the aggradation is of glacial age, and accordingly the rejuvenation is of interglacial age. ZEUNER (1945, p. 26) pointed out that, to state it more exactly, aggradation began when, toward the end of an interglacial, conditions became colder, and rejuvenation set in as soon as the climate became milder again, i. e. still under cold conditions. This type of river terraces is generally known as glacial-climatic terraces. Glacial-climatic terraces have provided valuable evidence for the chronology of the Pleistocene. Their significance is hardly less than that derived from directly glacial evidence.

The changing conditions of the Pleistocene, however, have affected the fluvial cycle still in another way. The changes of sea-level, due to glacial eustasy, were changes in fluvial base-level. The vertical amount and the duration of these oscillations were sufficient to cause rejuvenation and aggradation of the rivers, at least in their lower courses. ZEUNER (1945, p. 21) coined the term "thalassostatic terraces" for such terraces. Contrary to glacial-climatic terraces they are cut during the time from an interglacial climatic optimum to a glacial minimum (falling sea-level), whereas aggradation takes place during a rising sea-level after a glacial minimum.

When analyzing the Pleistocene history of the lower Somme, DE LAMOTHE (1918) nearly 40 years ago, clearly visualized the effect of a changing sea-level on river behaviour. Afterwards other rivers have been studied from this point of view. Nevertheless thalassostatic terraces still constitute a neglected chapter of Pleistocene as well as of physical geology. Few textbooks mention this type of terraces, although changes in base-level have long been recognized as an important cause of terrace formation.

II. General considerations

As compared with climatic-terraces thalassostatic terraces have received relatively little attention. As far as I am aware only one modern textbook of physical geology gives an adequate theoretical discussion of river behaviour as affected by an oscillating sea-level, *i. e.* B. G. ESCHER's *Grondslagen der Algemene Geologie,* 7th ed. etc. (1948, p. 193—4, fig. 257).

ESCHER arrives at the paradoxal (his own term) conclusion that both a falling and a rising sea-level result in renewed valley cutting. Indeed, erosion may occur in both cases. However, this does not happen in the same area, which seems to be neglected in ESCHER's discussion. A falling sea-level causes erosion in the lowermost river course, because the former sea-bottom left by the regressing sea does generally not correspond to the graded river profile. A rising sea-level, on the contrary, causes erosion higher upstream, owing to the shortening of the river. At the same time aggradation occurs in the lowermost part of the river, because the stream velocity decreases to zero. Then a delta starts to form. Although ESCHER does mention this important point in the text, he fails to account for its effect in his figure, from which his conclusions are derived.

Let B_1C_1 be the graded profile corresponding to a sea-level A_1B_1 (fig. 1a). Then, according to ESCHER, a higher sea-level A_2B_2 will ultimately result in the new graded profile B_2C_2. However, this applies only in case no aggradation occurs downward of B_2, and it is very unlikely that this will actually happen. As the result of erosion upstream of B_2, a certain amount of load becomes available and this will be deposited downstream of B_2. Consequently the graded profile is no longer B_2C_2, but has shifted a short distance seaward [1]. Assuming that the amount of load is sufficient to counterbalance the effect of the rising sea-level, the new base level will be at B_2' (fig. 1b) and the new graded profile will be $B_2'—C_2'$. The shore line shifts only the horizontal distance from B_1 to B_2' and the intersection with the former graded profile is at D. This means that aggradation seaward of B_2 leads to aggradation upward of B_2 as well. Just like the situation in fig. 1a represents an extreme case (no deposition at all), fig. 1b represents the other extreme (although much more likely to be realised), in which maximum deposition occurs.

In an intermediate case, when there is not a sufficient rate of deposition to counterbalance the effect of the rising sea-level and consequently the sea invades over the delta unto B_2'', the new graded profile will be $B_2''C_2''$ (fig. 1c). The intersection of the former with the new graded profile now occurs at D'. Just like B_2'' holds an intermediate position between B_2 and B_2', D' holds an intermediate position between B_2 and D. It should be noted, however, that D' always is upstream of B_2.

The effect of deposition may also influence the course of events actually happening during a falling sea-level. ESCHER's figure 257 (see fig. 2a) assumes a steep slope below the sea-level A_1B_1. Let B_1C_1 again be the corresponding graded profile, then a fall in sea-level to A_3B_3 will result in

[1] ESCHER's fig. 257, from which fig. 1a has been taken, represents a river course of more than 1000 km and a sea-level change of 40 m. It will be seen that it may as well be applied to a small sea-level rise and a short river tract, but for the steep slope in the higher part, which does not materially affect our reasoning.

a new graded profile B_3C_3. The intersection with the former profile of equilibrium is at D. The horizontal shift of the shore line is from B_1 to B_3. Valley cutting occurs between D and B_3.

However, if the sea is withdrawing from a very shallow area, for instance a delta formed during a preceding high sea-level, the shift in the shore line will be appreciable: B_1B_3' (fig. 2b). As compared with the former

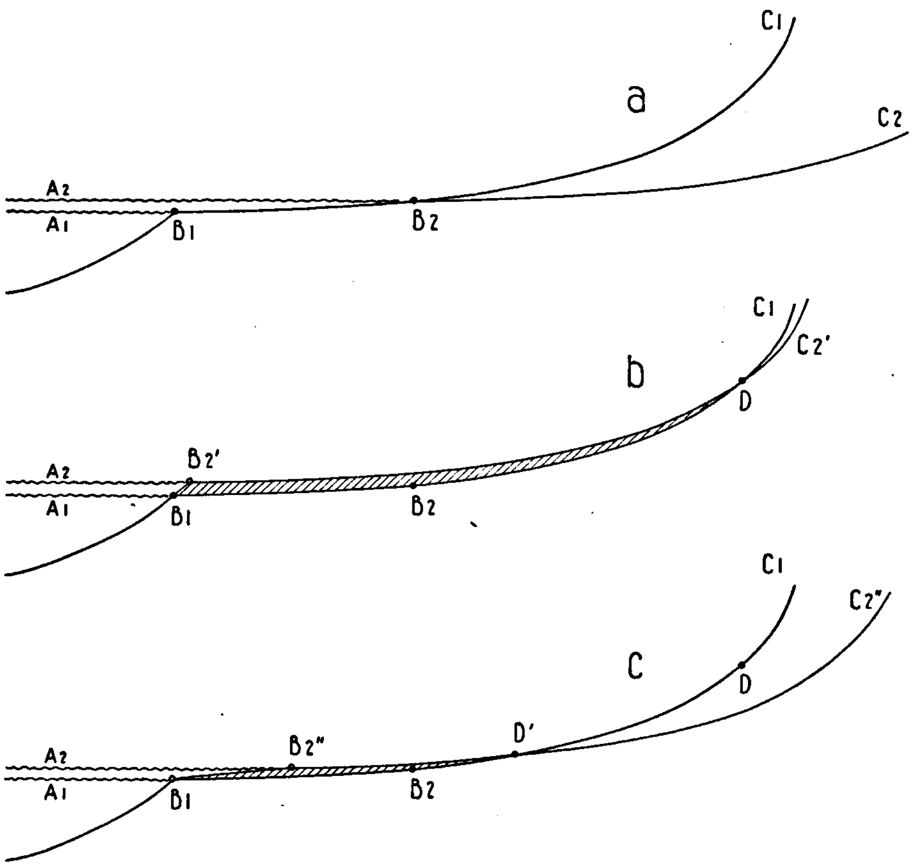

Fig. 1. The graded river profile as affected by a rising sea-level.

graded profile, the new one is not only lowered, but has also shifted more seaward. Consequently the intersection point D' is now much downward of D. The erosion downstream of D' yields new load to the river and as this is carried downstream the river may again be lengthened. Therefore the whole graded profile tends to travel still more seaward and accordingly point D' is again shifted downstream.

Perhaps is is unnecessary to remark that in the above discussion, apart from the changing sea-level, all other factors involved are supposed to have remained constant.

We now may formulate our conclusions as follows:

(1) the adaption of a river to the changed conditions of a rising sea-level tends to aggradation in the lowermost course, and to valley cutting upstream of that area;
(2) the adaption of a river to the changed conditions of a falling sea-level tends to valley cutting in the lowermost course, and to aggradation upstream of that area.

It will be seen that there is enough field evidence to support these conclusions.

Erosion and deposition occur at the same time during a rising sea-level

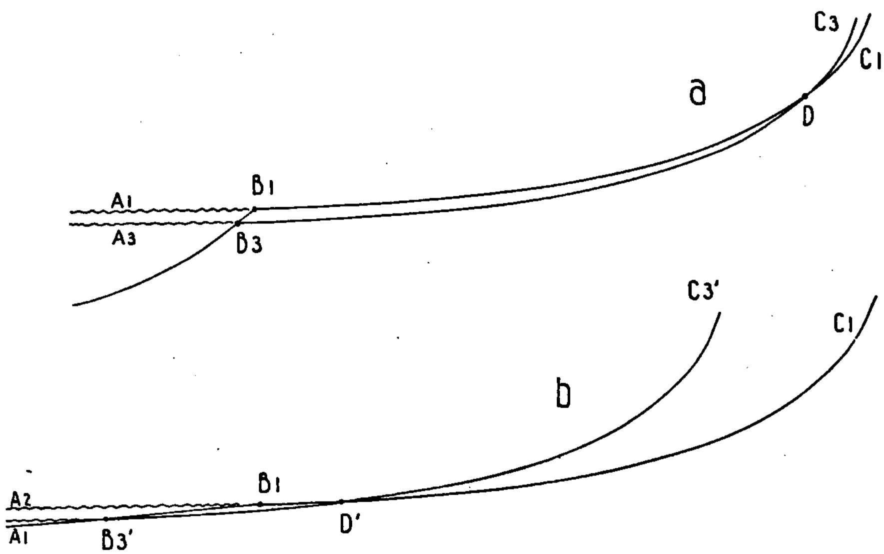

Fig. 2. The graded river profile as affected by a falling sea-level.

as well as during a falling sea-level. The relative position of erosion and deposition becomes inversed with a change in the direction of the sea-level movement: with a rising sea-level valley cutting occurs upstream of aggradation, whereas with a falling sea-level valley cutting takes place downstream of aggradation In fig. 1c le point D' (or D in fig. 1b) marks the lower limit of valley cutting, and the upper limit of aggradation. In fig. 2b point D' marks the lower limit of aggradation and the upper limit of valley cutting.

It should be noted that the intersection point D' (or D) does not hold a constant position. Assuming for a moment that fig. 1a represents a very small, instantaneous rise in sea-level, then indeed B_2C_2 is the new corresponding graded profile. However, immediately some material will be removed along B_2 and thus the new graded profile is shifted seaward. This means that the intersection point travels upstream from B_2 along B_1C_1. It can easily be inferred from fig. 1 that the intersection point travels the more upstream, the more the shore line retains its original geographical position. In the same way point D' travels downstream with a falling sea-level as may be seen from fig. 2. It does the more so, the more the shore line recedes.

The conclusions derived hereof may be formulated as follows:

(1) with a rising sea-level the aggradation proceeds upstream;

(2) with a falling sea-level the aggradation proceeds downstream.

As a matter of fact, alternating conditions of aggradation and rejuvenation may result in the formation of terraces. The terrace formation proper (i. e. the valley cutting phase) is connected with a falling sea-level in the lowermost river course and with a rising sea-level higher up. Both are the result of a change in sea-level. However, it appears that ZEUNER (1945, p. 21) when coining the term thalassostatic terraces, only considered the terrace formation in the lowermost part of the river. From a theoretical point of view this may be wrong. For practical reasons much can be said in favour of such a restriction, as will be clear from the following paragraph. I shall therefore use the term thalassostatic terrace in this restricted sense denoting only terraces formed in the lowermost river course as the result of a lowered sea-level.

III. Pleistocene thalassostatic terraces

Complications

Thalassostatic terraces may have come into existence at any time in the past when a lowering sea-level receded from an area suitable for terrace formation. The changing sea-level of the Pleistocene epoch, however, especially favoured the formation of such terraces. From obvious reasons they are best studied in the lower course of several Pleistocene rivers, particularly in deltas.

Our assumption made in the preceding paragraph, that apart from the oscillating sea-level, all other factors normally involved in terrace formation remained constant, does not apply under the changing conditions of the Pleistocene. As a result, many complications are introduced.

The first of these is that terrace formation is a normal phenomenon under Pleistocene conditions, even without changes in sea-level. The changes in weathering, load and run-off alone are sufficient to effectuate a change from deposition to valley cutting. This is particularly the case in the middle course of rivers in the periglacial belt. Such glacial-climatic terraces occur along large parts of many rivers in the periglacial belt of Europe between the northern limit of the Alpine and the southern limit of the Scandinavian glaciations. It is generally accepted that the conditions prevailing in the middle course of rivers in this area lead to glacial deposition and interglacial valley cutting, as is confirmed by paleontological evidence in many instances.

It will be seen that the glacial-climatic terrace formation essentially shows the same trend as terrace formation due to changes in sea-level upstream of the deltaic area. Only in the lowermost river course a falling sea-level results in valley cutting, and a rising sea-level in aggradation. However, upstream of that restricted near-mouth (deltaic) area, eustatic and climatic changes tend to affect the river in the same way. It is for this reason that the term thalassostatic terraces is restricted here to such terraces in the lowermost part of the river.

A second point introducing complications in the normal development of terraces under fluctuating sea-level conditions during the Pleistocene is the rate of these fluctuations. It can hardly be expected that enough time ever has been available to establish conditions of equilibrium. Normally conditions already changed long before a new graded profile had been reached. As a result knickpoints occur in many profiles, as has already been pointed out by DE LAMOTHE as early as 1918.

Most students of Pleistocene sea-levels believe that, apart from the fluctuations caused by glacial eustasy, the sea-level has in general been falling since the end of Tertiary times. In other words every interglacial high level should have been lower than the preceding one. Stable areas, or areas believed to be stable, seem to afford abundant evidence of this. Indeed it is remarkable to see how many marine terraces with nearly constant levels occur along widely separated coasts. In delta areas such a fall in sea-level should manifest itself in a sequence of river terraces at lower levels the younger they are. Although this situation is seldom met with, owing to factors unrelated with the nature of the Pleistocene, it is clear that the idea of a general lowering in sea-level is not disastrous for the conception of thalassostatic terraces.

As thalassostatic terraces are the result of relative movements of land and sea-level crustal movements may interfere in their formation. The effect of tectonic movements, being unrelated with the sequence of Pleistocene events, should of course be taken into account when studying Pleistocene deltas.

Among isostatic crustal movements two types should be distinguished. The first is due to isostatic readjustment of the crust to the loading and unloading of the glaciated areas. This, of course, is directly connected with the most characteristic Pleistocene phenomena. Judging from the evidence afforded by the present-day isostatic rise of Scandinavia, we may assume that the zero line separating the interglacially emerging area from the subsiding area more or less coincides with the maximum extension of the ice sheet which caused the disturbed equilibrium. This means that deltas within the periglacial belt, such as the Rhine delta, were emerging during the growth of a Scandinavian ice cap and subsiding during its waning. In other words this isostatic readjustment tends to accentuate the movements of sea-level. In the formerly glaciated area the two effects are opposite, but this needs not to trouble us, because such areas are unsuitable for the formation of large deltas.

A second type of isostatic crustal movements may be due to the extra load of the delta itself. Whereas this seems to be an important factor in deltas growing out into rather deep water, for instance the Mississippi delta or the Nile delta, it seems very doubtful whether this also applies to deltas growing out into shallow shelf seas, such as the Rhine delta. If in the latter case the thickness of the delta sediments excels the original water depth, it seems much more probable that the delta formation is the result of subsidence, and not the subsidence the result of the delta formation.

Whether subsidence occurs as the result or as the consequence of delta building, it is a normal accompanying phenomenon in delta formation. The effect of subsidence on thalassostatic terraces is worth our attention because it introduces a rather serious complication. As a consequence of a falling sea-level the corrosive power of the distributaries would be enhanced. Every stream tends to cut a trench for itself. After the sea-level has come to rest a graded profile may eventually be re-established if time permits. In the lower course of a river this seems not beyond possibilities. The streams would then proceed to widen the channels by lateral erosion. The former delta surface would then become a broad terrace cut by the trenches. A renewed rise in sea-level would lower the gradients of the streams in the channels by the building of minute deltas. This process will gradually proceed upstream. Under stable conditions, with an interglacial high sea-level lower than the preceding one, the channels would only be partly filled, but under conditions of subsidence this process will eventually be continued until the valleys would be filled to the brim. Thereafter the deposition spreads as a blanket over the former terrace surface, which becomes buried. With the next lowering of sea-level the process begins anew. As it is unlikely that the distributaries will hold the same position as at the onset of the preceding fall of sea-level the resulting structure of a subsiding delta built up under conditions of an oscillating sea-level, will be as is shown, in a simplified form, on the cross-section of fig. 3. It may be seen from fig. 3 that sections encountered in borings show several grades of completeness of the record. *A* represents a more or less complete sedimentary cycle, especially when it is situated in the lower part of the delta, where the aggradation sets in early. *B* and *C* are both incomplete: in *B* the upper part of the sequence is lacking, in *C* the lower part. *D* represents a very incomplete section of one cycle. It should be born in mind that nowhere occurs a truly uninterrupted sequence of deposits, due to the continuously shifting distributaries. A temporarily halt in the fall of sea-level may result in a terraced valley if enough time is availabe for lateral erosion (fig. 3, upper valley).

ZONNEVELD's (1948) sections through a part of the combined Rhine-Maas delta in the southeastern Netherlands show indeed the type of delta structure referred to above, although this does not mean that the alternating aggradation and valley cutting stages revealed by his sections are entirely the result of fluctuations of sea-level. Tectonical movements have been involved in the fluviatile history of the region described by ZONNEVELD. It should be possible to trace the picture farther downstream if sufficient borings would carefully be investigated.

The interrelationship of the sections from the northern Netherlands, dated by means of pollenanalyses (BROUWER, 1948) is understandable solely on the basis of the structural picture of a subsiding delta shown in fig. 3. However, the material suitable for pollenanalysis is too scanty to trace the picture in full. Heavy mineral investigations seem to promise rapid and reliable results, as soon as a correlation can be established between the floral zones distinguished and the mineralogical composition of the sediments. This line of approach seems to be a most promising one in order to arrive at a better understanding of the history of the Rhine delta.

Sedimentary sequences

Until recently it was generally accepted in this country that coarse river deposits should represent glacial conditions and fine grained deposits interglacial conditions. Indeed the well known clay deposits of Tegelen and

Neede yield abundant floral and faunal evidence for a temperate climate. The interrelationship of climate and grain size of the coarse deposits is more difficult to establish because of the unfossiliferous character of the latter. In a former paper (BROUWER, 1948) it has been shown by means of detailed pollenanalytical investigations that there is no ground for such a simple relation between climatic conditions and grain size. The question may be raised whether any relationship exists at all.

From the discussion presented in part II it may be inferred that the deviation between the graded and the factual longitudinal river profile in the lower course is at maximum during the lowest sea-level. When with a rise of sea-level fluviatile deposition sets in the velocity and the transport powers of the river will be at maximum. Consequently coarse deposits will be laid down at the river mouth. As the aggradation gradually proceeds upstream the profile will appraoch a state of equilibrium and at the same time the velocity and transporting power will decrease. Consequently the grain size and the amount of deposition will also decrease.

Therefore we may conclude that the aggradation keeping pace with a rising sea-level will gradually decrease in grain size. Of course many excep-

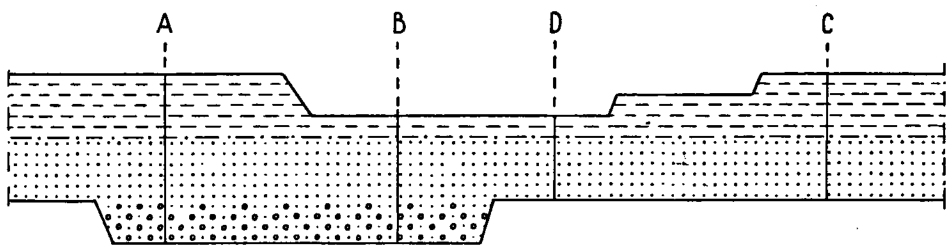

Fig. 3. Idealised cross-section of one sedimentary cycle in a subsiding delta.

tions may occur owing to local conditions, but as a general approximation the rule will hold well. Finally the fluviatile sequence may be covered by subaqueaceous sediments.

Several instances of such large scale "graded bedding" can be found scattered in the descriptions of deltas and of valley deposits in lower river courses.

Conclusions

It seems appropriate to conclude that in the lowermost parts of Pleistocene rivers their behaviour with regard to aggradation and valley cutting has largely been controlled by sea-level oscillations due to glacial eustasy. The river tends to valley cutting with a lowering of sea-level and to aggradation during a rise in sea-level. It should be born in mind that upstream the reverse phenomena occur, as sea-level oscillations and changing climatic conditions result in aggradation during a falling sea-level or glacial conditions respectively. In the opposite case valley cutting would occur with a rising sea-level or under interglacial conditions.

The sequence of events in both parts of the river course under consideration seems closely connected, as the erosion in the middle course disposes the river of the load to be deposited in the lower course.

A second point of interest is that aggradation in the lower course. and in particular the building of Pleistocene deltas, has largely taken place with a rising sea-level, *i. e.* under conditions leading to an interglacial climate. It is true that the aggradation sets in under rather cold conditions, but this happens in the lowermost area of deposition, which is normally flooded by the interglacial transgression. The higher part of the delta is mainly built up under interglacial conditions. Indeed it is a remarkable phenomenon that the paleontological evidence in such areas in the periglacial belt of Europe (Rhine, Thames, Somme) points generally to temperate climatic conditions. The long pollendiagrams from the northern Netherlands, some of which comprise several hundred meters, do not show any evidence of glacial conditions (BROUWER, 1948). This is in striking contrast to the many floral and faunal remains indicative of cold conditions, found in the typical glacial-climatic terraces in the middle course of many German rivers.

Fig. 4 summarizes the sequence of events as dependent on sea-level changes. As no uniformally adopted definition of glacial and interglacial ages exists, two different interpretations are indicated. The time span of the rising sea-level, included by FISK in the following interglacial and by

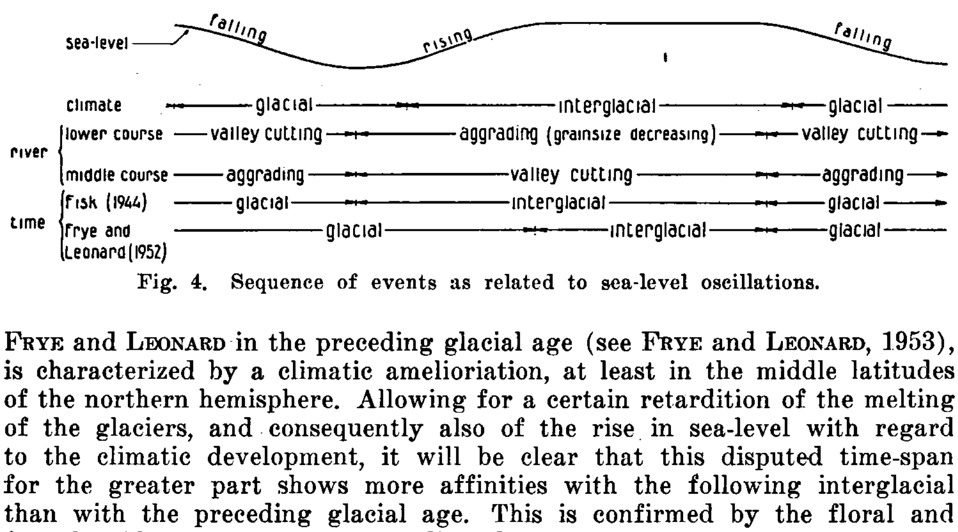

Fig. 4. Sequence of events as related to sea-level oscillations.

FRYE and LEONARD in the preceding glacial age (see FRYE and LEONARD, 1953), is characterized by a climatic amelioriation, at least in the middle latitudes of the northern hemisphere. Allowing for a certain retardition of the melting of the glaciers, and consequently also of the rise in sea-level with regard to the climatic development, it will be clear that this disputed time-span for the greater part shows more affinities with the following interglacial than with the preceding glacial age. This is confirmed by the floral and faunal evidence in the corresponding deposits of western Europe.

IV. Stratigraphical appreciation

As Pleistocene thalassostatic terraces are directly related to the changing sea-level they constitute an important link in establishing a world wide chronology of the Pleistocene epoch, as

(1) the changing sea-level itself is a function of the growth and disappearance of glaciations, certainly one of the most characteristic features of the Pleistocene, and

(2) sea-level oscillations are manifested the world over in the same way independent of differences in climatic conditions, facies or fossil contents.

Of course the marine record proper should be of still greater value, but geologists living in an interglacial age are faced with the difficulty that the present high sea-level conceals much of its own story. Under these circumstances thalassostatic terraces may be a valued substitute in ordinary field investigations. However, the most complete record is to be expected in subsiding deltas, where the marine deposits due to high sea-levels as well as the fluviatile aggradation related with the rising sea-level should be preserved. These most valuable sequences are revealed only by subsurface methods. So far only few deltas have been investigated from this point of view.

It is beyond the scope of the present paper to make any attempt towards a world wide stratigraphy based on sea-level fluctuations as reflected in the fluviatile record. Only a few remarks will be made to show the results to be expected along this line of investigation, and the problems to be met with.

No doubt, one of the best known deltas studied in relation to the changing Pleistocene sea-level, is the Mississippi delta. RUSSELL (1940), building upon FISK's (1938) investigations, distinguished five sedimentary cycles, each of which is the result of a rising sea-level, succeeding rejuvenation due to a low sea-level. It is noteworthy that the same number of transgressions occurs in the Rhine delta (BROUWER, in press), although in North-America, as well as in Europe the number of established major glaciations is less than five. Traces of earlier glaciations may be concealed or even destroyed by later glaciations. Proof of their existence may be found in the fluviatile or marine record, if they lack in the glacial record.

As early as 1918 DÉPÉRET recognised the same number of high sea-levels in the Mediterranean, the classic area of the study of Pleistocene high sea-levels. Although in later years a tendency can be observed of increasing the number of high sea-levels in the Mediterranean, it remains to be proven which of these represent interglacial high sea-levels and which are merely temporarily halts in a falling or rising sea-level. Therefore areas of fairly continuous sedimentation seem more promising in tracing the ups and downs of Pleistocene sea-level. The deltas of the Rhône and of the Nile should prove to be of special importance in this respect. SANDFORD and ARKELL (1939) studied the Nilotic terraces. Their results seem to confirm the conclusions reached with regard to the second half of the Pleistocene in other Mediterranean areas. In regard to the older Pleistocene history much remains to be done.

Many small sedimentary basins along the coasts of the Mediterranean are awaiting detailed investigtaion. The present status of our knowledge has been summarized by MOVIUS (1949) and I may refer to his important paper for more details.

In temperate Europe the lower parts of the Thames (KING and OAKLEY, 1936) and of the Somme (DE LAMOTHE, 1918; BREUIL & KOSLOWSKI, 1931/1932) are among the best studied examples of thalassostatic terraces. Indeed the lower Somme valley may well be considered to be the birth-place of the conception of this type of river terraces. Both areas are of special interest, because they have yielded abundant paleontological evidence in favour of an interglacial age of the main aggradation phases. Moreover both areas are of particular importance as, at least for the greater part, their successive terraces have not been burried under younger deposits. Therefore they afford better opportunities for detailed study than can ever be possible in strongly subsiding areas, as for instance the Rhine delta. It is true that in the higher part of the Rhine delta a terraced surface is still exposed. However, its development is so much affected by tectonical movement and to a lesser degree by the moving ice-front, that it will hardly be possible to connect its history with sea-level oscillations. Perhaps it will be possible to establish such a correlation for the youngest terraces. The slight valley cutting observed in the braided system of the Rhine at the transition from Late Glacial to Holocene, may be explained as the result of adaptation to the postglacial rise in sea-level.

Owing to the fact that in Germany attention has been focussed on glacial-climatic terraces, the concept of thalassostatic terraces seems to have been somewhat neglected. However, several studies reveal evidence in favour of terrace formation controlled by sea-level fluctuations. Glacial valley cutting and interglacial aggradation can be inferred from HORNE's (1912) and GRAHMANN's (1931) contributions on the lower Elbe. Recently ILLIES (1952) and WOLDSTEDT (1952) have pointed out that it is impossible to assume a glacial-climatic origin for all terraces along the German rivers.

The most obvious reason for the usefulness of thalassostatic terraces in establishing a world wide chronology of the Pleistocene epoch, is to be found in the fact that everywhere on earth fluviatile aggradation and erosion is controlled by the same sea-level oscillations. I may cite SMIT SIBINGA's (1949, 1953) investigations of the rivers of the Sunda Plat as fine examples of the application of thalassostatic terraces to problems of chronology in regions far away from the main centres of Pleistocene glaciation. No doubt future investigations will show that thalassostatic terraces are of much more importance for a world wide Pleisotcene chronology than are the much better studied glacial-climatic terraces.

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