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MAJOR EPEIROGENIC AND EUSTATIC CHANGES SINCE THE CRETACEOUS, AND THEIR POSSIBLE RELATIONSHIP TO CRUSTAL STRUCTURE

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ABSTRACT. It is contended that the Earth's surface has undergone a progressive increase in average relief since the close of the Cretaceous, having been subjected to a series of major, intermittent epeirogenic movements of opposite sense in the continents and oceans in addition to much local movement of a more random sort. A series of transgressions and regressions discernible in the Tertiary stratigraphic record is attributed to eustatic rises and falls of sealevel consequent upon changes in the cubic capacity of the ocean basins. Superimposed upon these oscillations is a gradual regression of the seas from the continents which is interpreted as the result of progressive oceanic subsidence rather than an increase in the Earth's radius. A tentative attempt is made to account for the epeirogenic changes in terms of Dietz' theory of crustal structure based on the spreading of the sea floor. It is proposed that the continents have risen as a result of isostatic adjustment following centripetal transfer of sial from the margins by convection currents in the upper mantle, subsequent to the attainment of a position of dynamic equilibrium, while regional subsidence of the ocean floor is probably a consequence of changes in the mantle accompanied by stretching of the basaltic layer.

INTRODUCTION

At the close of the Cretaceous Period the Earth underwent one of the most striking changes in its history, marked by an extensive withdrawal of the sea from the continents and by the extinction of numerous groups of Mesozoic animals. Subsequent history, better documented than any preceding era, has an essential faunal and geological unity, with the Earth changing gradually toward its present condition as the continental outlines of today became progressively blocked out.

Students of modern geological history have tended to confine themselves to such specialized aspects as land geomorphology, diastrophism, stratigraphy, and oceanography, and there has been inadequate interplay among them. The author has attempted to build up a synthesis from certain striking results acquired in different disciplines and propounds the view that many features of Tertiary and Quaternary history can be related to one unifying factor, a succession of major epeirogenic movements of opposite sense in the continents and oceans. A tentative attempt is made to explain these movements in terms of Dietz' (1961) model of crustal evolution. Though interpretation in such a broad topic is bound to be speculative and open to dispute at many points, it is believed that the questions posed are valid ones which deserve serious attention. This work may also serve as a review, though references are made as brief as possible to avoid a paper of inordinate length.

CONTINENTAL UPLIFT

Uplift in continental regions is inferred from such varied evidence as the presence of marine sediments and terraces at altitudes above present sealevel, erosional platforms, and river terraces and nick points. It may also be deduced for limited areas from the character of the clastic detritus in basins of sedimentation.

Many workers have appreciated that there has been a considerable increase in relief throughout the world within the past few million years. Flint (1957) claims that the average elevation of the continents since the early Miocene has increased from less than 1000 to some 2500 feet. This uplift, which is abundantly documented, has affected a whole variety of terrains ranging from Tertiary orogenic belts to old shield areas such as the Canadian and Scandinavian Shields, and a significant proportion of it has taken place in the late Pliocene and Pleistocene.

In studying Tertiary uplift on a regional scale, the most promising approach involves consideration of the high-level erosional platforms throughout the world (peneplains or pediplains according to interpretation). Taking as his starting point the spectacular African surfaces, beveled across a variety of rocks and extending for vast distances, King (1950) has attempted a worldwide correlation. He recognizes a series of surfaces, increasing in altitude with age, produced by alternating phases of uplift and pediplanation. The oldest and highest surfaces (Laurasian-Gondwana) were formed in the late Mesozoic and fall outside the scope of this paper. A long period of late Cretaceous and Lower Tertiary pediplanation was followed in mid-Tertiary times by a significant phase of uplift, producing the most striking surfaces in Africa, South America, India, and Australia. Then came a further period of pediplanation followed by several cycles of late Tertiary and Quaternary uplift and erosion. The uplift was accompanied by a certain amount of regional warping so that an exact matching of platform heights between continents is not to be expected.

Certain aspects of King's work may be criticized. Dating of high-level surfaces is notoriously imprecise and the implications of more or less exact age equivalence may be unjustified. Moreover, certain correlations may be faulty. Thus the 2500- to 3000-foot surfaces of the Grampian Highlands of Scotland is regarded as a pre-Tertiary (Laurentian) feature. But this surface continues into the Western Highlands and cuts across the Hebridean igneous complex of Tertiary age.[1] However, the basic idea of progressive, intermittent uplift, alternating with phases of erosion to base level throughout the Tertiary, appears to be sound and finds support in many regional studies.

A fuller appreciation of what may be involved in uplift on the continental scale comes from King's more detailed comparison of Brazil and southern and central Africa (1957). He demonstrates a remarkable parallelism in the late Mesozoic, Tertiary, and Quaternary history of the two regions. Following the late Cretaceous-Lower Tertiary denudation cycle there was a period of uplift in the late Oligocene, producing the widespread "African" and "Sul Americana" surfaces that stand at an altitude of around 3000 feet above sealevel. Denudation and sedimentation commenced and were followed by another major phase of uplift in the late Pliocene and early Pleistocene. Minor Quaternary cycles of denudation, sedimentation, and uplift can be recognized.

Uplift was not uniform but concentrated at the margins of the continents. The older surfaces descend seaward because of marginal downflexure while in

[1] This error has since been corrected (King, 1962).

the continental interiors there are large shallow depressions that received a small thickness of Tertiary and Quaternary sediments. Movements in the same sense seem to have been repeated within the same structural belts. This notion of repeated movements along old lines finds an echo in Australia (Hills, 1961).

Turning our attention now to Pleistocene interglacial marine terraces, we come across a most interesting fact, namely, that there is a progressive increase in altitude with age, with the oldest, Sicilian, terrace lying at about 100 m (Zeuner, 1959; Fairbridge, 1961). The heights of the terraces are essentially uniform throughout the world, and there is no evidence that traces of lower, older shorelines have been destroyed over extensive areas by higher, younger ones. If the altitudes reached by the sea in successive interglacials are due solely to deglaciation, the interglacial climates should have been progressively warmer the greater their age. This interpretation is not supported by the available evidence. Therefore there must have been a gradual eustatic fall of sealevel superimposed on the pronounced eustatic changes due to alternating glaciation and deglaciation (see Fairbridge, 1961, fig. 10).

The notion of a progressive regression of the sea can possibly be extended back into the Pliocene from evidence, for example, in Britain (George, 1955). A 650-ft late Pliocene platform, locally bearing residual marine deposits, is well established in southern England. Older, higher platforms of late Tertiary age have been recognized by a number of workers in southwest England, Wales, and the Pennines, and some correlation by height has been attempted with the mainland of Europe; they are regarded by some as marking the positions of former shorelines. The equivalence in levels has led to the suggestion that the fall in sealevel was eustatic, but detailed correlations with Europe are difficult, and the area involved is rather small on a world scale so that the possibility of regional warping cannot yet be discounted. Similar considerations apply to Weaver's (1961) claim that erosion surfaces around the Caribbean signify a late Tertiary eustatic lowering of sealevel.

To summarize, there appears to have been a progressive overall emergence of the continents since the early Tertiary. This has been accomplished in the Quaternary essentially by a eustatic regression of the sea, though there has been crustal warping locally. The possible role of eustatic regression in the Tertiary must await consideration of the sedimentary evidence, but reasons will be given for believing that a significant proportion of the uplift is due to regional epeirogeny. It is clear that uplift has been differential and some continental areas have indeed had a long history of subsidence (the Mississippi and North Sea Basins are just two well documented examples). Two important characteristics may be noted here. Movement has often been concentrated in old structural zones and has been intermittent, periods of uplift alternating with longer periods of erosion toward base level.

Much confusion reigns in the literature on the relationship between orogeny and epeirogeny in the Tertiary mountain building. Billings (1960) has stressed that mountains arise directly as a result of uplift rather than lateral compression, contrary to what seems to be implied in much published opinion (the belief is perpetuated by Emiliani and Geiss, 1957). Furthermore, there is much to be said against the classic view that the late Tertiary uplift is due simply to the isostatic recovery of deep sialic roots developed by subsidence and compression in Lower Tertiary orogenic belts.

There is no simple relationship between the amount of late Tertiary uplift and the distribution of the young orogenic belts. Epeirogeny was worldwide and affected "unstable" belts and old massifs alike. Some of the greatest uplift took place in regions where Mesozoic and Tertiary orogenic movements were negligible (e.g. Colorado and Abyssinian Plateaux). Conversely, such active regions as Indonesia, Melanesia, and the Caribbean could be regarded as Lower Tertiary orogenic belts that have failed to rise sufficiently to produce continental mountains. The pattern of Upper Tertiary epeirogeny seems, in fact, to be independent of the distribution of younger orogenic belts not merely in the Caribbean and Indonesia (Kuenen, 1950) but in southeast Europe (Mouratov, 1960).

Similar conclusions have been reached for the Mediterranean alpine belts by de Sitter (1953) and Pannekoek (1960), who fail to find the intimate relationship between Tertiary orogeny and subsequent uplift demanded by the classic tectogene theory.

A number of workers, including Bucher (1933), Gilluly (1949), King (1955), Billings (1960), and Pannekoek (1960) have expressed doubt whether there is a clear separation in time of orogenic and epeirogenic movements. Certainly the late Pliocene-Pleistocene fold phases in the Himalayas, California, and elsewhere are contemporaneous with major epeirogeny elsewhere. It seems quite probable that both types of movement are the local expressions of similar subcrustal forces in different tectonic regimes ("stable" and "unstable" belts).

Finally, mention should be made of the evidence of fossil plants and animals, which clearly indicates that temperatures have decreased more or less steadily throughout the Tertiary (Durham, 1959). This accords well with the notion of a gradual increase in continental relief during this time.

OCEANIC SUBSIDENCE

Guyots and Atolls

Guyots or flat-topped seamounts are widespread in the Pacific and occur less commonly in the Atlantic. The Pacific guyots tend to be confined to limited belts such as the Mid-Pacific Mountains and the Gulf of Alaska, with summits at average depths of about 800 and 500 fathoms respectively (Shepard, 1959, fig. 78). A group of seamounts including guyots occurs in the Atlantic north of the Bermuda Rise and rises to depths of from 550 to 850 fathoms. Guyots have also been discovered south of the Azores, on the flanks of the Mid-Atlantic Ridge (Heezen, Tharp, and Ewing, 1959).

The most thorough description and discussion of guyots is due to Hamilton (1956), who studied those in the Mid-Pacific Mountains west of the Hawaiian Islands. They consist of basaltic volcanoes with truncated tops at depths ranging from 500 to 1100 fathoms. The tops show signs of erosion, with basalt cobbles and gravel sometimes associated with sediments containing shallow-water fossils mid-Cretaceous or younger in age. Hamilton argues cogently that isostatic adjustment, oceanic sedimentation, and compaction of sediments under basalt are all of minor importance and cannot account for the main Tertiary subsidence. Nor are there good grounds for believing that there has been a vast addition of juvenile water to the oceans since the late Mesozoic, as Revelle (1955) has suggested. Hamilton quotes authoritative estimates suggesting that addition of juvenile water during this time could not account for a rise in sea-level of more than 50 to 100 meters. Hamilton concludes that the evidence of the guyots indicates regional subsidence due to the operation of subcrustal forces. The varying heights of the truncated summits is partly a function of age, partly of regional warping. The importance of this latter factor is underlined by the discovery by Menard and Dietz (1951) of a guyot summit in the Aleutian Trench at 1380 fathoms, in contrast to the much shallower guyot depths elsewhere in the Gulf of Alaska.

Shepard (1959) gives a good recent discussion of atolls. Several drillings have revealed thicknesses of several thousand feet of shallow-water Tertiary and Quaternary fossiliferous limestones in such widely separated areas as the Marshall Islands and the neighborhood of Borneo and Okinawa. The fullest data come from Eniwetok Atoll (Ladd and others, 1953). A great thickness of proved Quaternary. Miocene, and Eocene calcareous sediments were found resting at a depth of 4154 ft on olivine basalt. There seems no question that the sediments are in situ. Darwin's famous theory has therefore been thoroughly vindicated, and the evidence of the atolls wholly supports that of the guyots in indicating slow regional subsidence. The link between atolls and guyots is now well established, as both Bikini and Eniwetok occur in intimate association with a number of guyots. Some of the latter could actually be regarded as aborted atolls, reef growth having failed to keep pace with subsidence.

Marginal Downflexure of Continents, Subsidence of Landmasses and Formation of Deep Trenches

There are widespread indications of marginal downwarp of the continents from such varied evidence as seaward descent of erosion surfaces and warping of marine terraces, seaward dip and thickening of Cretaceous and Tertiary sediments, coastal truncation of Tertiary orogenic belts, foundered offshore land areas, and, more controversially, submarine canyons (Umbgrove, 1947; Lees, 1953). It becomes, indeed, " . . . difficult to avoid the conclusion that marginal areas have subsided to form part of the present deep-sea floor" (Kuenen, 1950, p. 147).

The best documented example of marginal downflexure is the coastal plain and continental shelf of the eastern United States (Lees, 1953: Billings, 1960). Both the pre-Cretaceous land surface and the Lower Tertiary Schooley Peneplain dip gently seaward from the Appalachians, and a wedge of Mesozoic and Tertiary sediments thickens in the same direction. On the continental shelf to the south, the Bahamas form a high platform of calcareous sediments probably all of shallow-water origin (Newell, 1955). Newell finds the conclusion unavoidable that this part of the shelf has subsided over $2\frac{1}{2}$ miles since the early Cretaceous.

Further north in the Atlantic, there is good evidence of Tertiary downflexure of the east coast of Greenland (Wager, 1947).

Along the west coast of Africa, from Senegal to Angola, a coastal wedge of Cretaceous and Tertiary sediments dips gently seawards and thickens to over 20,000 ft, while the mid-Tertiary erosion surface is warped in the same direction (Umbgrove, 1947; Lees, 1953; King, 1957). The northwest coast of Africa coincides approximately with a hinge. Inland of the hinge are a series of terraces increasing in elevation with age. Seaward, on the continental shelf/slope, are further terraces, the lowest being the oldest (Bourcart, 1938, 1950). These latter terraces, of Upper Tertiary age, are warped seaward, the amount of warping increasing with age.

A comparable seaward warping of Upper Pliocene and Quaternary marine terraces is reported by Emery (1958) off the coast of California, where there is independent evidence of subsidence in the last few million years. In the Indian Ocean the Lower Tertiary Deccan Traps appear to have been downwarped into the Arabian Sea (Lees, 1953). Lees also cites the case of Japan where the eastern half of the fold zone has a monoclinal structure dipping gently toward the ocean.

Many geologists have been impressed by indications that parts of the present deep sea floor close to the continents mark the sites of former land areas. Attention will be confined to continental areas that appear to have subsided since the Cretaceous.

Some of the best evidence comes from "Melanesia", that part of the southwest Pacific between and north of Australia and New Zealand. There has been a widespread measure of agreement since the pioneer work of Marshall that a considerable continental area has subsided in the Tertiary (Bryan, 1944; Browne, 1947; Reed, 1949; Umbgrove, 1947; Gilluly, 1955). The area falls outside the so-called Andesite Line, which has been traditionally accepted as marking the true geological boundary of the Pacific. Australia is evidently an "incomplete" subcontinent (Bryan, 1944). The islands of New Zealand, with rocks ranging in age back to the Precambrian, have been regarded by most Australian geologists as the isolated remnants of a much more extensive landmass. The thick Jurassic graywackes in New Zealand must have been derived from land to the west (Arkell, 1956). For such reasons as these a former continental area, "Tasmantis", is presumed to have lain between Australia and New Zealand. Break-up of the continent may have commenced in the Lower Tertiary (Bryan, 1944), but the main movements may well have been as recent as the late Pliocene and Pleistocene (Browne, 1947), a time of intensive block faulting. Glaessner (1952) questions the notion of a catastrophic breakdown of a former landmass but even he considers that the Tasman Sea developed only as a unified geomorphological feature in late Tertiary or Quaternary times, suggesting an acceptance of some degree of subsidence.

In the Indonesian region subsidence of a formerly more extensive land area commenced during and after the Upper Miocene orogeny (Kuenen, 1950). Thus Tertiary tectonic structures are cut obliquely by the coastlines, indicating that the latter postdate the sedimentary troughs and folds. The facies of the Tertiary rocks denotes the existence of former extensive zones of denudation and that shallow seas were widespread until the main orogeny. To

Kuenen the conclusion appears unavoidable that elevation of land and subsidence of troughs went on hand-in-hand.

On the other side of the Pacific, off the coast of California, the evidence of depths of hilltops, basin floors, and sills points to downwarping and downfaulting of a continental borderland from (probably) late Miocene times onwards (Emery, 1958).

The Caribbean is at the present day a deep or moderately deep sea. The two most recent assessments of its geological history are unequivocal. In the view of Woodring (1954), "it is quite evident on ordinary geological grounds that a considerable part of the Caribbean Sea was land during the Cretaceous, and that at least some of this land was still land during the Eocene". For Butterlin (1956, p. 349), "the Caribbean Sea is an ancient continent which fed the sedimentation of the adjacent basins and collapsed later. It is the only acceptable hypothesis today".

Turning next to the Indian Ocean, Wiseman and Sewell (1937) claim that the triangle of the Arabian Sea was downfaulted and submerged to its present depth in Pliocene and post-Pliocene times. The granitic rocks of the Seychelles, hundreds of miles from the nearest continent, are most reasonably explained as the remnants of a subsided continental block[2] (Reed, 1949).

Upper Tertiary subsidence brought an end to the old landmass of "Tyrrhenis" in the western Mediterranean. Relics of this landmass are found in the old granitic massifs of northeastern Spain, Sardinia, Corsica, and Maurès-Esterel in the south of France. It was also in Upper Tertiary times that subsidence brought into existence the deep basins of the eastern Mediterranean and the Black Sea (Mouratov, 1960). Indeed, Pliocene land deposits have been dredged at a depth of 6000 ft from the floor of the Black Sea (Holmes, 1944, p. 420). As in Indonesia the present coastlines cut abruptly across Lower Tertiary fold belts.

Subsidence in the Lower Tertiary is claimed to have destroyed "Scandia" in the North Atlantic (Umbgrove, 1947).

The deep oceanic trenches, generally characterized by negative gravity anomalies, also appear to be features developed essentially in Tertiary or post-Tertiary times. The Indonesian trenches are dated as Upper Tertiary (Kuenen, 1950) or end Tertiary-Quaternary (van Bemmelen, 1949). The series of trenches extending from Japan to the Marianas are late Cretaceous to Tertiary (Hess, 1948), and the east Aleutians Trench early Tertiary in age (Menard and Dietz, 1951). A Tertiary age is also assigned to the trenches in and around the Caribbean (Rutten, 1935; Hess, 1938). Stratigraphical data suggest that the island of Barbados has undergone a complex epeirogenic history, subsiding into the deep sea in the Lower Tertiary and rising again to form land subsequently (King, 1959).

Submarine Canyons

In view of all this diverse evidence of oceanic subsidence since the Cretaceous there should be less reluctance to admit the possibility that at least some submarine canyons (Shepard, 1948) have been excavated subaerially.

[2] This interpretation has recently been confirmed by Miller and Mudie (1961), who have determined a Cambrian age for the granites.

Much of this reluctance is due to the fact that at one time it was believed that the canyons were excavated wholly in the Quaternary. The consequent suggestion that sealevel had risen some 10,000 feet due to deglaciation was generally regarded as highly implausible. Shepard has since sought (1952) to evade this difficulty by means of a composite theory involving subaerial excavation, submergence, and the action of turbidity currents over a long period extending well back into the Tertiary. The upper portions of the canyons, he proposes, were produced by subaerial erosion and kept clear by the periodic movements of submarine landslides or turbidity currents. The shallower trenches on the continental rise are turbidity current excavations through the canyon deltas. The maximum elevation required for subaerial excavation is perhaps 6000 ft but is often much less. Indeed, uplift of only 1000 ft could account for most canyons provided the upper portions of the canyon walls consist of formations postdating the excavation.

It is perhaps significant that the best explored canyons, off California and in the western Mediterranean, have characteristics most readily accounted for by subaerial erosion. Thus they resemble land canyons in possessing steep walls cut through hard material, including granitic and metamorphic rocks, and in possessing winding courses, V-shaped cross profiles, and tributaries. The great canyons off the west coast of Corsica correspond exactly with land valleys (Shepard, 1959). It may be added here that in both regions there is independent evidence of pronounced late Tertiary submergence. Furthermore, one of the old objections, that the gradients of submarine canyons are steeper than equivalent valleys on the land, loses its force when viewed in the context of marginal downwarping of the continents.

Shepard (1952, 1959) has presented information throwing considerable doubt on the capacity of turbidity currents to excavate deep valleys with tributaries through even unconsolidated rock. Nevertheless, his most recent view is a cautious one, that although the Californian and Mediterranean canyons were almost certainly cut subaerially, there is no strong evidence as yet for worldwide submergence of canyons as a whole.

Conclusions

Clearly, evidence of oceanic subsidence is widespread but it has not yet been proved everywhere. In the open ocean guyots and atolls are not ubiquitous, though this does not necessarily mean that subsidence of the sea floor has not taken place. Not many sectors of the continental margins have yet been explored in sufficient detail, though it must be borne in mind that many coasts probably lack a marginal strip of Tertiary sediments because of late Tertiary block faulting. Obviously the evidence of submarine canyons is critical, for they are worldwide in distribution. At present the ubiquitous or near-ubiquitous character of the subsidence must remain a plausible hypothesis. It is hard to avoid the conclusion, however, that a significant overall deepening of the oceans has taken place since the Cretaceous.

It is profitable to enquire whether or not the subsidence has been intermittent in character. The data from the Eniwetok boreholes are highly suggestive in this respect, since a marked stratigraphical break has been proved between the Eocene and Miocene. More such data from neighboring atolls are badly needed. Much marginal subsidence took place in the late Tertiary and Pleistocene, the time of intense epeirogeny and block faulting on the continents. In so far as the connection proves to be intimate, it would imply that the subsidence was accomplished in a series of short pulses. This is in fact suggested by the presence of marine terraces dating back into the Tertiary in the sea off Africa, California, and elsewhere.

MARINE TRANSGRESSIONS AND REGRESSIONS

Introduction

The Tertiary stratigraphical record reveals, as is well known, a succession of marine transgressions and regressions frequently correlated with cycles of sedimentation. The belief that these marine migrations are due to eustatic changes of sealevel may be traced back to Suess (1906), who observed that successive transgressions in different parts of Europe took place at specific times.

In this section a brief survey will be attempted covering widely separated parts of the world. Western Europe and the Mississippi Gulf will be treated in some detail as examples of well documented areas. The works utilized for these regions include Gignoux (1950), Davies and Elliot (1957), Bornhauser (1947), Cooke, Gardner, and Woodring (1943), Rainwater (1960), and Stephenson (1928). Sample areas for the rest of the world have not been selected to favor any particular hypothesis. Attention is concentrated on regions that have not suffered major orogenic deformation during the Tertiary. Recognition of eustatic changes is bound to be affected by regional epeirogeny, but if given transgressions and regressions are found to be essentially contemporaneous over widely separated areas in different continents, they may be reasonably regarded as resulting from worldwide rises and falls of sealevel. The major features of the world picture have been checked by reference to Kummel (1961) and the paleogeographic atlas of H. and G. Termier (1960).

It is true that transgressions and regressions may locally be slightly diachronous (Davies and Elliot, 1957), but this is not likely to affect the general picture, which is concerned with major movements of the sea.

Description

An outline of the late Cretaceous background is desirable before the Tertiary is considered.

Upper Cretaceous.—The Upper Cretaceous marks the time of a vast transgression, one of the greatest the world has known (Bucher, 1933; Gignoux, 1950; Umbgrove, 1947). At its maximum extent, for example, the sea covered nearly half of the United States (Dunbar, 1960). The transgression is often regarded as beginning in Cenomanian times, but it could reasonably be taken as commencing in the Albian or even earlier. At all events, there was a progressive spread of the sea over the continents, with minor interruptions marked by local unconformities between successive stages, culminating in the Maestrichtian. Vast spreads of chalk and other limestones testify to land that was restricted in extent and subdued in relief.

Transition from the Cretaceous to the Tertiary.—Precise comments on this subject have been vitiated by the uncertainty surrounding the stratigraphical position of the Danian stage. There now seems to be general agreement, however, that the Cretaceous-Tertiary boundary should be taken between the Maestrichtian and the Danian (Symposium on the Cretaceous-Tertiary boundary: 21st Internat. Geol. Congress, 1960).

The change from the Cretaceous to the Tertiary is marked by a major, worldwide regression, at least as pronounced as the Upper Cretaceous transgression, after which the sea has never returned to its former extent. For example, the maximum Tertiary submergence of the United States never exceeded 10 percent and averaged only about 3 percent (Dunbar, 1960). The regression seems to have been much more rapid than the preceding transgression, though it was anticipated in certain places such as parts of southwest Europe and the Western Interior of the United States, as is indicated by the presence of Upper Maestrichtian nonmarine deposits. This may merely be a consequence, however, of regional uplift.

Almost all areas show the effects of this regression, which is expressed in various ways. There is widespread development of a nonsequence of varying magnitude and an erosion horizon containing material derived from the underlying Cretaceous, generally marking an abrupt change in sedimentary facies. This is true, for instance, of Denmark and southern Sweden (Berggren, 1960), Poland (Pozaryski and Pozaryska, 1960), Western Europe (Gignoux, 1950), the Gulf coastal plain (Rainwater, 1960), and Japan (Matsumoto, 1960). There is a stratigraphical gap between the Cretaceous and Eocene of the Atlantic coast of the United States. Sometimes the boundary is marked by a sharp lithological break in a continuous marine series of fairly constant facies, as, for instance, in the Indian subcontinent (Nagappa, 1960) and the Majunga Basin of Madagascar (Lys, 1960). In the former area the sea withdrew completely from eastern India, Burma, and Tibet, and became isolated from the Mediterranean Tethys (Davies, 1940). Only in a few places in Indonesia is there no stratigraphical break between the Cretaceous and Tertiary (van Bemmelen, 1949). In the Western Interior of the United States there is a continuous transition in nonmarine beds with, however, a pronounced faunal break (Clemens, 1960; Jeletsky, 1960; Spieker, 1960).

Angular unconformity at the boundary is uncommon and major geographical patterns were often little altered, apart from the withdrawal of the sea, which tended to return subsequently along the old seaways. This is true, for instance, of Europe and North Africa (Gignoux, 1950), North America (Dunbar, 1960), and northern Asia (Kummel, 1961).

All this evidence provides very good grounds for believing that the transition from the Cretaceous to the Tertiary was accomplished by a eustatic fall in sealevel.

Lower Paleocene.—The fullest northwest European succession is in the region of Denmark and Scania, where the type Danian occurs. With regard to the Anglo-Belgian-Paris Basin, the Lower Paleocene is best developed in Belgium, where it is represented by littoral marine deposits resting on an eroded surface of chalk. It occurs in isolated pockets in the Paris Basin but is absent from England.

In the Mississippi Gulf the Lower Paleocene marks the greatest extent of the Tertiary seas. It is developed as shallow-water terrigenous clastics, whereas further to the east, in Florida, it is represented by a calcareous facies. Such a sedimentary pattern was to remain essentially constant throughout the Tertiary.

North Africa compares with the Gulf region in that the Lower Paleocene is comparatively widespread, though much less so than the Upper Cretaceous. In general, though, the seas were rather restricted in extent at this time. There are locally indications of separate Danian and Montian transgressions.

Upper Paleocene.—In the Anglo-Belgian-Paris Basin the Upper Paleocene commenced with a marine transgression and ended in a regression, as indicated by nonmarine beds at the top of the succession. In the Gulf region the lower part of the Upper Paleocene (= Middle Paleocene of Rainwater (1960)) consists largely of black shales signifying a deepening of the sea from Lower Paleocene times. In the upper part a regressive nonmarine facies is widespread.

The Upper Paleocene transgression is also well marked in Pakistan (L. M. Davies, 1940). The end-Paleocene regression is a worldwide phenomenon (A. M. Davies, 1934).

Lower Eocene.—The Lower Eocene is generally transgressive (Davies, 1934). This may be indicated by the presence of marine beds resting on freshwater Paleocene, as in England and southern Japan, or by overlap onto Cretaceous, as in northern France, northern Germany, parts of northern Italy, southern Spain and North Africa, Syria, and New Jersey.

The importance of this transgression is readily appreciated in England and Belgium, where the facies is one of open sea clays passing upward into marine sands, but in the Paris Basin it is much less apparent, much of the Lower Eocene consisting of nonmarine (Sparnacian) facies. In the Mississippi Gulf Lower Eocene transgresses over Paleocene, from which it is separated by a widespread unconformity.

The transgression served to restore the marine connection between Europe and Pakistan, broken at the end of the Cretacous (Davies, 1940).

Middle Eocene.—The Middle Eocene was the time of a major worldwide transgression during which the Eocene sea reached its maximum extent (A. M. Davies, 1934; L. M. Davies, 1940), with marine beds frequently resting on freshwater Lower Eocene or on pre-Tertiary rocks. The transgression brought about the isolation of the main continental masses, which seems to have led in its turn to a major differentiation of mammalian faunas. Locally the sea extended almost as far as the Maestrichtian sea, as in India (Davies, 1940), while in Western Australia the (undifferentiated) Eocene is slightly more widespread than the Upper Cretaceous (McWhae and others, 1958). There are places, however, where the Middle Eocene sea seems to have been more restricted than the Lower Eocene, as, for example, in the Gulf region and Egypt (Furon, 1960). The transgression left its mark in certain Tertiary orogenic belts, including the Caribbean (Woodring, 1954), southern California, and Indonesia (Davies, 1940).

Regarding the two regions selected for more detailed study, the effect of the transgression in Western Europe is variable. It was of major importance in the Paris Basin but is less well marked in England, whilst in Belgium most of the deposits were removed by erosion before the Ledian transgression in the Upper Eocene. The Middle Eocene sea may well have had a wide exent in the Baltic region and northern Germany, but deposits could have been largely removed by pre-Oligocene erosion.

There is an important nonsequence at the base of the Middle Eocene in the Gulf region. Bornhauser (1947) recognizes two transgressions based on the alternation of marine beds with lignitic sands and shales, but no unconformity is present.

Upper Eocene.—Considering the world picture, the Upper Eocene is generally regressive with respect to the Middle and overlaps the latter in very few places (Davies, 1934). The regression allowed the renewed cross migration of mammals among the northern continents. By the close of Eocene times the seas had become very restricted in extent.

In England and Belgium a Ledian transgression was followed by a regression, as indicated by nonmarine beds and a local stratigraphical break below the Oligocene. In the Paris Basin a further, Ludian, transgression is recognizable. Signs of an Upper Eocene transgression have also been recognized in the Gulf region, while the end-Eocene regression was a significant event throughout the Tertiary belts of the whole United States (Dunbar, 1960).

During the Paleocene and Eocene the sea had penetrated deep into North Africa, in the Saharan and Sudanese Gulfs, but retreated definitively at the end of the Eocene to a narrow belt bordering the Mediterranean (Gignoux, 1950; Furon, 1960). Farther round the coast the sea retreated definitively from Senegal after the Middle Eocene. The post-Middle Eocene regression marked the main stage in the blocking out of the Indian subcontinent, for subsequent transgressions were of minor importance (Davies, 1940). A widespread stratigraphical break between the Eocene and Lower Miocene in Western Australia suggests the possibility of an end-Eocene regression (McWhae and others, 1958).

Oligocene.—In many parts of the world the Oligocene is regressive compared with the Eocene. Little Oligocene is present in continental Africa and is largely confined to coastal belts in Somalia, East Africa, and Madagascar. Where both Eocene and Oligocene deposits are present, as in Egypt (Furon, 1960), the latter tend to be more restricted in distribution, though they are transgressive in Somalia. There are only restricted coastal deposits in India and Pakistan except in Sind and Baluchistan, where a calcareous facies is developed (Krishnan, 1956). In the Middle East (Lees, 1950) there is a widespread development of evaporites above the marine Eocene, and Oligocene is missing near the Arabian Shield. As already noted, it is absent also from Western Australia. This was a time of emergence in a number of orogenic belts, such as the Alps (in part), the Caribbean, southern California, and Indonesia.

In the *Lower Oligocene* there is some evidence of a new transgression. This is indicated in Belgium by marine sands passing upward into regressive facies at the top of the succession. The sea in England was more restricted than in the Eocene and the deposits are largely nonmarine, but there is a thin wedge of marine rocks in the Hampshire Basin deposited during the transgression. In northern Europe marine sands mark the beginning of a transgression that was to reach its culmination in the Middle Oligocene. In the Mississippi Gulf a little Lower Oligocene is present.

Following a minor end-Lower Oligocene regression came a transgression in the Middle Oligocene in Europe, the Gulf coast, and the Caribbean. Its effects are most pronounced in the Paris Basin and in northern, central, and eastern Europe, the sea extending as far as southern Russia. This vast spread of sea seems rather exceptional when viewed in the context of the world picture. It is rather uncertain, however, how much Eocene may have been removed by pre-Oligocene erosion.

A general and comparatively sudden retreat of the epicontinental seas took place in *Upper Oligocene* times, so that by the end of the period they had once more become very restricted in distribution. The sea withdrew definitely from the Anglo-Paris Basin and the northern embayment of the Mississippi Gulf, though in Belgium there was a minor transgression preceding the final regression. In northern Europe marine sands pass up into estuarine beds, whereas freshwater molasse deposition began in the southern and eastern European alpine belts following Middle Oligocene uplift.

Miocene.—Broadly speaking, following the late Oligocene regression the seas never returned to the same extent as in the Lower Tertiary. There was, however, an important transgression in the Lower Miocene. Subsequent to this time there set in a progressive general withdrawal of the sea from the continents, interrupted by comparatively minor transgressions.

The sharp contrast between the Lower Tertiary and Miocene is well seen in Europe, North Africa, and the Gulf region, the Miocene seas never penetrating far into the continental interiors.

Evidence of an important *Lower Miocene* transgression comes from many parts of the world. It had notable effects in Aquitaine and the Mediterranean alpine zone. For example, the Peri-alpine molasse trough was subjected to a slow invasion of the sea so that by Burdigalian times a continuous marine link had been established between the Rhone Valley and eastern Europe. Transgressive Lower Miocene is observed in several places round the coast of Africa, from Angola to Madagascar and East Africa (King, 1957; Furon, 1960); also on the south coast of Western Australia, where the sea reached almost as far as in Eocene times (McWhae and others, 1958). The transgression is well marked also in the orogenic belts of Indonesia (van Bemmelen, 1949), the Caribbean, and southern California.

By *Middle Miocene* times the sea had withdrawn definitively from Western Australia and much of the African coast, as also from the Himalayas (Krishnan, 1956). In the latter part of the Middle Miocene the marine molasse of the Peri-alpine trough was replaced by freshwater molasse. The middle Miocene in fact marked the beginning of a major phase of uplift in many Tertiary orogenic belts.

Elsewhere Middle Miocene sediments occupy the same areas as the Lower Miocene and actually transgress them in a few places. Thus in northern Europe the sea spread beyond the region of Denmark as the North Sea Basin subsided.

Generally speaking the *Upper Miocene* is markedly regressive compared with the Lower and Middle, though a minor transgression assumes importance locally, as on the Atlantic coast of the United States. This was a time of major upheaval of Tertiary orogenic belts. Southeast Europe witnessed the partial isolation of several brackish-water inland seas, while continental molasse troughs subsided *pari passu* with the uprise of European alpine ranges. A huge molasse foredeep developed in the Middle East following the withdrawal of the Middle Miocene sea (Lees, 1950), and the Mediterranean became isolated from the Indian Ocean. A comparable pattern is recognizable in the orogenic belts of North Africa, the Caribbean, California, and Indonesia, where the Upper Miocene tends to be missing or developed in regressive facies except in a few restricted basins.

By the close of Miocene times the epicontinental seas had withdrawn to a minimum so that there is a widespread stratigraphical break at the base of the Pliocene. Deposition had ceased in the western Mediterranean alpine troughs, and the present outlines of the continents were now broadly established.

Pliocene and Quaternary.—The Pliocene is generally regressive compared with the Miocene. An early Pliocene transgression, affecting only limited belts on the borders of the continents, was followed by a gradual regression, corresponding in time with a major phase of worldwide continental upheaval. This can be discerned from the sedimentary record in areas as widely separated as Italy and southeast Australia.

In Europe the Pliocene transgression was confined to parts of the Atlantic and Mediterranean seaboards. A very thin strip of marine Pliocene occurs along the Atlantic coast of the United States, whereas only nonmarine beds are found along the Gulf coast.

Disregarding the major eustatic changes associated with glaciation and deglaciation (Fairbridge, 1961), which are not relevant to the present investigation, Quaternary time marks a continuation of the late Pliocene regression.

Conclusions

The stratigraphical subdivisions adopted in the foregoing survey are sufficiently precise to allow certain broad generalizations. The widespread synchronism of major transgressions and regressions leads reasonably to the postulation of periodic eustatic rises and falls of sealevel. This could probably have been deduced from a consideration of the Anglo-Belgian-Paris Basin and the Mississippi Gulf alone. These two areas exhibit a remarkable series of parallelisms in time, and sedimentary facies is very similar, fresh- and brackish-water sands and clays passing offshore into marine sands and deeper water clays. Alternations of these different rock types give rise to distinctive sedimentary cycles reflecting the rise and fall of sealevel.

Obviously this subject could be pursued in greater detail. For example, bearing in mind the Paris Basin, the Upper Eocene might be represented by separate Ledian and Ludian transgressions. The general picture of major eustatic phases is unlikely, however, to be affected.

Spread of the sea over the continents has inevitably been affected by regional epeirogeny, which must have had an important influence in determining the extent to which the land was transgressed. In the Mississippi Gulf, for instance, the Paleocene contradicts the general rule in extending further inland than the Eocene. This could well have resulted from a greater rate of subsidence of the basin at the beginning of the Tertiary.

Another important point emerging from the survey is that superimposed on the oscillatory pattern of transgressions and regressions there has been a progressive withdrawal of the sea from the continents since the Cretaceous, so that later transgressions have generally failed to reach as far as their predecessors. Thus the Eocene is regressive with respect to the Upper Cretaceous, the Oligocene slightly so with respect to the Eocene in many areas, the later Miocene compared with the early Miocene and Oligocene and the Pliocene with the Miocene (see, for instance, the paleogeographic maps of Wills (1951) and Schuchert (1955)). The Paleocene would appear to be exceptional in being generally more regressive than the Eocene, though it could be regarded as marking the start of a slow transgression that was to reach its culmination in the Middle Eocene.

This progressive withdrawal of the sea was probably more pronounced than appears today, as the older the formation the greater the likelihood of its having been removed by intra-Tertiary erosion. In other words, location of former shorelines becomes increasingly uncertain with age. There is an instructive case in East Anglia to illustrate this point. Here the Pliocene and Quaternary "Crag" deposits transgress Chalk and Lower Tertiaries on the margin of the North Sea Basin. The basal Pliocene beds contain, however, reworked Miocene marine fossils (Davies, 1934), suggesting that the implication of a Pliocene sea transgressing beyond the limits of the Miocene sea is probably fallacious.

The possible link-up between oceanic deepening and progressive eustatic regression should clearly be explored. Attention must also be paid to the role of the continents in view of the evidence of widespread differential uplift. This leads us to a consideration of the relationship between epeirogeny and eustasy.

EPEIROGENY AND EUSTASY

Classic ideas on the cause of eustatic changes of sealevel have been adequately summarized elsewhere (Bucher, 1933; Umbgrove, 1939; Kuenen, 1950; Fairbridge, 1961) and need not be reviewed in detail here.

Two different causal processes have been given serious attention. Firstly it has been suggested that transgressions are the results of displacement of sea water by oceanic sedimentation, an idea that may be traced back to Suess. Kuenen and Fairbridge have made it clear, however, that this process is quite inadequate to account for major transgressions and leaves regressions unexplained. The alternative supposes that changes in sealevel are due to epeirogenic movements in both positive and negative sense, resulting in changes in the cubic capacity of the ocean basins. This theory, in that both transgressions and regressions are readily accounted for in terms of a well known process, is more plausible and more widely accepted today. It is well expressed in Bucher's opinion 36 (1933): "The major eustatic movements of the sea are thus the result of changes in the vertical distance between mean levels of ocean floors and continental surfaces".

In regard to the progressive regression of the sea since the end of the Cretaceous there is a third theory to consider, based on the recognition that the Earth may be expanding, with the continents being "drifted" apart or dispersed in consequence (Egyed, 1957; Carey, 1958; Heezen, 1960). More specifically, it is claimed by Heezen that the oceanic sectors are under tension and marked by a worldwide rift system. Holmes (1959) has seen in this a mechanism to account for the gradual eustatic regression in the Quaternary superimposed on the changes in sealevel due to periodic glaciation (see also Weaver, 1961). Now the present author's thesis is that this Quaternary regression is merely the accelerated continuation of a process operating throughout the Tertiary. Extrapolating Holmes' idea, this implies a significant amount of continental drift since the Cretaceous. Though the author is not opposed to the possibility of drift at an earlier time, he considers it unlikely that there has been substantial movement in the Tertiary, for the following reasons:

In the first place there is the purely negative evidence from stratigraphy. It cannot seriously be contended that the present distribution of Tertiary rocks, unlike, for instance, the late Paleozoic glacials, demands bringing the continents closer together. Much has been made by the proponents of Tertiary drift of the distribution of mammals and marine invertebrates. Simpson (1943), in a highly entertaining article, effectively demolishes any suggestion that mammal distribution cannot be accounted for in terms of the present configuration of oceans and continents. Durham (1950, 1952) is equally decisive in rejecting drift as an explanation of the distribution of early Tertiary marine invertebrates. Chaney (1940) argues from the variations in Eocene "isoflors" that the broad relationships of land and sea were similar to those of the present day. Both Durham and Chaney maintain that the poles have not shifted position appreciably during the Tertiary. A vast amount is known about Tertiary organisms, and the concordant opinions of these three authorities warrant respect.

Cox and Doell (1960), in a comprehensive review of paleomagnetic evidence, conclude that the post-Eocene results are impressive and offer very strong evidence against substantial polar wandering or continental drift. Although the Permian and Carboniferous results suggest the likelihood of a drift of North America from Europe, those from the Mesozoic and early Tertiary fail to give any consistent picture and are susceptible to widely different interpretations.

In view of the good evidence of widespread oceanic deepening since the Cretaceous, we seem to have an adequate source for the regression without having to look further afield.

So far it has been assumed that the continents have played a purely passive role in the regression. This may be true to some extent for the Quaternary, but there is clear evidence that large parts of the continents have been subjected to considerable differential uplift. This is well documented for the late

Tertiary and, accepting the fundamental points of L. C. King's work (1950, 1957), for the earlier Tertiary as well. Any upward movement of the continents would serve to enhance the regression under discussion. One could even propose the extreme view that it is due essentially to fairly uniform concerted movements of the continents rather than to oceanic subsidence. Such a view, however, seems highly implausible and is not supported by various detailed considerations. For example, the Mississippi Basin has been a region of more or less continuous downwarp since the late Jurassic. For such important regressions as those between the Eocene and Oligocene, Oligocene and Miocene, and Miocene and Pliocene, one would have to invoke major reversals of this trend.

One promising line of approach in evaluating the relationship between continental and oceanic epeirogenic movements is to attempt an estimate of the amount of eustatic change implied by various transgressions and regressions and the amount of Tertiary and Quaternary oceanic subsidence.

Kuenen (1950) states that in most periods of geological time a rise of sealevel of 50 meters would effect a transgression over one-quarter, and a rise of 100 meters over one-third of the surface of the continents. He considers that the more extensive transgressions probably did not involve a rise of more than 200 meters. Fairbridge (1961) regards it as unlikely that absolute eustatic oscillations over very long periods normally ranged above 200 to 500 meters.

In regard to oceanic subsidence, Kuenen (1950) estimates that deepening of the Indonesian, East Asiatic, Caribbean, and Mediterranean oceanic basins in the Tertiary would have effected a eustatic lowering of sealevel of some 60 to 80 meters. The present author has attempted a rough calculation of the lowering due to subsidence of those parts of the Pacific floor where guyots are known to occur (Shepard, 1959, fig. 78). Accepting a mean depth of the guyot summits of about 700 fathoms (= 1.25 km) and an area of 11.8×10^6 square km, subsidence from late Cretaceous or early Tertiary times onward would have effected a eustatic fall of about 40 meters (given the area of the oceans as approximately 360×10^6 square km).

Thus the sealevel must have fallen since late Cretaceous times by at least 100 to 120 m. This is almost certainly a considerable underestimate. No account has been taken of the presence of guyots in the Atlantic nor of those extensive oceanic areas where there is no positive evidence. Furthermore, the evidence of marginal downwarping of extensive parts of the continents has to be considered. A figure of 250 m or more might seem a fairer estimate (cf. Fairbridge, 1961, who estimates a possible overall lowering of about 200 m during the time in question).

Accepting this figure of 250 m as being of the right order, the differences between this and the heights of the oldest widespread Tertiary erosion surfaces will give the amount of absolute continental uplift. Taking, for example, a height of about 3000 ft for the "African" and "Sul Americana" surfaces, we deduce an uplift of over 2000 ft for extensive sectors of the African and South American continents since the mid-Tertiary.

We turn now to a consideration of the possible temporal relationships between continental uplift and oceanic subsidence. Dealing firstly with the best documented phase of movement, the late Pliocene and Pleistocene have been marked by considerable worldwide continental uplift associated with block-faulting, volcanism, and, in certain young orogenic belts, with folding. This correlates in time with a period of considerable subsidence in many marginal oceanic zones including the deep trenches associated with island arcs. According to Stearns (1945) the late Tertiary and Pleistocene was also a time of major volcanism and collapse of parts of the Pacific Basin, as indicated by deeply drowned platforms and valleys off the Hawaiian Islands. The Eniwetok boreholes passed, moreover, through several hundred feet of shallow water Quaternary limestones.

Further back in time, preceding the early Pliocene transgression, the late Miocene marks a further phase of widespread continental uplift, faulting, and folding associated, it would seem, with a worldwide fall of sealevel that may be attributed to contemporaneous submergence of oceanic sectors. More tentatively, the mid-Tertiary uplift evidenced by widespread erosion surfaces might correlate with the pronounced eustatic regression that took place in the late Oligocene. The end-Cretaceous regression may have been a consequence of the initiation of significant ocean deepening as evidenced by Pacific atolls and guyots. Evidence of widespread uplift of the land is not so clear, though certain areas affected by the Laramide Orogeny appear to have risen at about this time.

This brief survey seems to allow at least the tentative suggestion that movements in an opposite sense of large parts of the continents and oceans were linked in time.

Though the gradual Tertiary-Quaternary regression of the sea can be regarded as explained adequately in terms of progressive oceanic subsidence, the periodic transgressions seem to demand that various sectors of the ocean floor have risen at different times, so displacing water onto the continents. This is plausible enough when it is borne in mind that certain parts of the continents have had a recent history of relative subsidence within a framework of net uplift. Similarly it may be postulated that oceanic swells have developed, moving in a sense opposed to the general tendency. Possible examples are the mid-oceanic ridges (see Note Added in Proof, below). Comparison has been made between these apparent rift structures and the East African Rift System (Ewing and Ewing, 1959; Heezen, 1960). Now the rifts of the latter have been attributed to axial epeirogenic uplift (Cloos, 1932), so that if the comparison is valid and the oceanic ridges are, as is probable, partly Tertiary in age, these sectors of the oceans may have undergone some uplift since the Cretaceous. The presence of guyots south of the Azores suggests, however, a certain degree of subsidence locally.

A further point of interest is the relative speed of the Tertiary transgressions and regressions. According to Suess (1906) the usual pattern is for a slow transgression to be succeeded by a relatively rapid regression. It could indeed be argued that this is true for the late Cretaceous, also perhaps for the Paleocene-Middle Eocene transgression and the Upper Eocene regression and for the Oligocene as a whole. But this would be at the expense of ignoring the minor regressions.

Accepting, nevertheless, for the sake of argument, the proposition that there is an overall degree of temporal asymmetry in the eustatic changes, an illuminating comparison can be made with the epeirogenic behavior of the continents. It appears from the work of King (1950, 1957) and others that comparatively rapid and short-lived phases of uplift are succeeded by longer periods of comparative stability. If, as is tentatively proposed above, there is some sort of connection between these movements and subsidence in the oceans, it might be expected that the latter took place in a series of short pulses. Such pulses would have the effect of inducing fairly rapid regressions of the sea from the continents. Here indeed is a matter worthy of closer investigation.

In summary, it is proposed that there has been a generally progressive increase in average relief of the crust since the late Cretaceous, with the continents having suffered overall epeirogenic uplift and the oceans overall deepening, the movements taking place probably in a series of pulses. Oceanic subsidence has had the effect of inducing an overall regression of the sea from the continents, which has been interrupted by a series of transgressions resulting from the displacement of water by limited uplifts of parts of the ocean floor.

EPEIROGENY AND CRUSTAL STRUCTURE

Structure of the Crust

Recognition that the continents and oceans have fundamentally different structures is now well established on the basis of seismic and gravity data (Woollard, 1959). For most workers the base of the crust is defined sharply by the Mohorovičić Discontinuity, underlain by material with a seismic velocity of about 8.1 km/sec, but Dietz (1961) differs in preferring to confine the true crust to the sialic continents. Broadly speaking it has become generally accepted that the continental crust consists of an upper, low velocity "granitic" layer underlain by an intermediate "basaltic" layer, the total thickness being about 35 km. The ocean floors have an average of about 0.3 km of unconsolidated sediments underlain by about 2.0 km of mixed volcanics and lithified sediments and a 5.0-km basaltic layer.

According to Woollard (1959) there is close agreement between results derived from the study of Bouguer anomalies and the velocity dispersion of surface earthquake waves, and good correlation exists between topographic elevation and crustal thickness. Isostasy has therefore been proved on a regional basis.

Possible Crustal Changes since the Cretaceous

Bullard (1954) states what may fairly be described as the orthodox argument of geophysicists, that given this picture of crustal structure the oceans must be permanent, because continental-type crust cannot be converted into oceanic. It seems dubiously justifiable, however, to extrapolate backward in time from the present configuration. There are, in fact, a number of examples where a good case can be made out for invoking the loss of marginal continental areas to the oceans since the Cretaceous, provided one excludes the possibility of considerable continental drift in the late Tertiary.

(*1*) *Melanesia.*—As has been pointed out in an earlier section, strong geological grounds exist for maintaining that a considerable continental area has foundered into deep water. Officer (1955) has found, nevertheless, that the floor of the deep Tasman Sea, between Australia and New Zealand, has an oceanic structure, whereas New Zealand (20 to 30 km) and Fiji possess only a thin continental-type crust. From this he argues that New Zealand has been built on an isolated strip of continental crust. This implies that it has been surrounded by deep ocean since the Precambrian. This seems an untenable conclusion, especially as the Southern Alps are left without an adequate source for their sediments. It seems far more reasonable geologically to accept that deep foundering has been associated with the loss by some process of sialic material.

(*2*) *Caribbean Sea.*—The I. G. Y. Report in the Transactions of the American Geophysical Union for 1959 records a good correlation between topographic elevation and crustal thickness. An oceanic-type crustal structure is present under the Cayman Trough, south of Cuba, where some 5 km of water are underlain by only 5 to 6 km of crust. Southward, under the Nicaragua Rise, the crust thickens to probably 20 to 25 km (or possibly more). Cuba also has a thick continental crust thinning rapidly southward below the Yucatan Basin. It would be extraordinary if the Cayman Trough marked a thin strip of original oceanic crust isolated in the midst of continental. Loss of continental crust would, on the other hand, elicit subsidence by means of isostatic adjustment.

(*3*) *Mediterranean, Red, Black, and Caspian Seas.*—Unfortunately, there are as yet no seismic data on crustal thickness for the Mediterranean, but on gravity grounds it is regarded as tending to oceanic-type in structure (Ewing and Press, 1955; Mouratov, 1960). Girdler (1958) has discovered a belt of positive gravity anomalies in the deep axial trough of the Red Sea. He interprets this fact as signifying a young tensional fracture widened and healed by basalt intrusion from below the crust.

In the deep trench of the Black Sea (M. Mouratov, personal communication) the granitic layer disappears. The crustal thickness is somewhat greater than the true oceanic, but the structures are very much alike, with a 10 to 12 km sedimentary layer overlying a similar thickness of basalt. The difference is regarded as due essentially to more intense sedimentation than in the open ocean. A similar structure has been found in the southern part of the Caspian.

Now the Caspian and Black Seas are isolated from the oceans and extend far into the interior of Eurasia; according to Mouratov (1960) they owe their present morphology to late Tertiary subsidence. There is no geological reason for believing that they had an oceanic structure long before this time. Similarly, although the Mediterranean lies on the site of an ancient seaway, the geological evidence does not favor the continued presence there of a deep ocean. As has been pointed out earlier, an old landmass, Tyrrhenis, foundered into the western Mediterranean as recently as the late Tertiary. Many of the Mesozoic and Tertiary sediments in and around the sea, away from the main orogenic belts, are of normal epicontinental type (Arkell, 1956, p. 147).

(4) *Indonesia.*—The deep basins in the Indonesian region, which have also subsided in the Tertiary, appear on the basis of gravity data to be nearer oceanic than continental in structure (Kuenen, 1950). At least some of the deep trenches associated with island arcs are anomalous in lacking isostatic equilibrium, but gravity data suggest that the Mindanao Deep is underlain by thin oceanic crust (Worzel and Shurbet, 1955).

More generally, it follows from Woollard's (1959) recognition of the close relationship between elevation and crustal thickness that the continents are very closely circumscribed by oceanic-type crust. This is confirmed wherever detailed seismic work has been undertaken, as off the eastern coast of the United States (Heezen, Tharp, and Ewing, 1959), the Gulf of Mexico (Ewing and others, 1955), California (Shepard, 1959), and the western approaches of the English Channel (Hill and Laughton, 1954). The granitic layer thins abruptly to nothing at about the position of the continental slope, thus tending to confirm Shepard's (1948) view that the continental slope marks a fundamental fault structure. The consequence is that paleogeographers are left with embarrassingly little room to manoeuver. Partly as a consequence of the findings of geophysicists, there has been some tendency for geologists in the recent past to pare down the size of former landmasses foundered in the oceans, but it is apparent today that there is little space for even marginal strips. It becomes very difficult to avoid the conclusion that parts of the continental crust have been lost to the oceans.

Relationship of Epeirogenic Movements to Crustal Changes

The intimate relationship between crustal thickness and elevation, implying good isostatic compensation, and the pronounced epeirogenic movements discussed in this paper lead inescapably to the conclusion that there have been significant changes in crustal thickness and/or density since the Cretaceous. Two possible explanations are as follows:

(1) Changes have been effected between the crust and the upper mantle. There are two alternatives, depending on which model is preferred. A phase change from eclogite to basalt would lead to expansion and hence cause uplift (Lovering, 1958). Conversely, a change in the opposite direction would cause subsidence. Alternatively peridotite may be converted into serpentine, causing expansion, and vice versa (Hess, 1955).

(2) Sial has been transferred laterally at the base of the crust from the continental shelf to beneath the continents, with the consequent displacement of sima. This theory is economical in that it accounts for both continental uplift and marginal downflexure by one process. There are reasonable grounds for believing that this process has played an important role.

(a) As has been pointed out earlier, important phases of continental uplift appear to have coincided at least to some extent with marginal subsidence. The process could be a large expression of a phenomenon well known on a more local scale, namely, that subsidence of troughs of sedimentation is often intimately associated in time with the rise of neighboring geanticlines. The opposed movements may also be similar in general character. Thus Mouratov (1960) recognizes three distinct stages in the evolution of the eastern European alpine chains: a pre-orogenic stage marked by the uplift of flat arches of median massifs associated with the shallow sinking of inner zone depressions; a synorogenic stage in which deep elongate depressions (eugeosynclines) developed side by side with narrow geanticlines; and a post-orogenic stage characterized by uplift of the old geosynclines and the adjacent subsidence of intermontane troughs and "molasse" foredeeps. Such changes as these could best be accounted for by the lateral transfer of sial at the base of the crust.

(b) The continents have had a comparatively persistent freeboard since back beyond the Tertiary. Gilluly (1955) points out that, even with slower rates of erosion than operating at the present, continental relief would be reduced to very little, the sediments being carried out to sea, in only a few million years. He argues that, if isostasy is to be maintained, powerful currents must return an equal mass of subcrustal material to positions beneath the continents. Heezen (1960) maintains that light material has been carried from the oceans to beneath the continents by convection currents.

(c) There is a strong suggestion that the Pacific floor is underthrusting its borders. The marginal faults proved by earthquake studies dip, for example, toward and beneath the continents. In so far as Jessen (1943) is justified in postulating widespread uplift of continental margins, they could be accounted for by movement of sial from the oceans. Both of these points are made by Gilluly (1955).

This interpretation does not explain subsidence in mid-ocean, as there are no satisfactory geological grounds for advocating a loss of sial since the early Tertiary. Some subsidence could perhaps have been accomplished by stretching of the basaltic layer of the crust if the oceans are under tension, as Heezen (1960) and Dietz (1961) suggest, but probably most of it is the consequence of changes in the mantle.

A Possible Mechanism

Any attempt to explain epeirogenic movements in terms of subcrustal process will of necessity be highly speculative in view of the present inadequacy of knowledge. The author has been much stimulated, however, by a recent paper of Dietz (1961), who puts forward a model of crustal evolution based on the spreading of the sea floor in the comparatively recent geological past, to account for many of the facts acquired in the last few years by oceanographic researchers. His ideas are presented here in outline.

Large-scale thermal convection cells operate in the mantle and provide the primary diastrophic forces. The oceanic "crust" is almost wholly coupled with the convective overturn of the mantle, so that the sea floor marks the top of the convection cells. The median oceanic rises, which appear to be rift structures and are characterized by high rates of heat flow, represent the sites of upwelling or divergences, whereas the deep trenches adjacent to island arcs are located on downwelling sites or convergences. Rifts tend to develop in the continents where underlain by divergences.

It is considered that the crust proper is confined to the sialic continents, which may have no basal basaltic layer so that there may be an abrupt transition from "granite" to eclogite. They provide a density barrier to convective circulation, so that the latter shears beneath them, and have been carried apart by viscous drag until they have reached a position of dynamic balance overlying a convergence. It follows, if no expansion is invoked, that the oceans are mostly under tension and the continents mostly under compression. Clastic erosion products carried to sea are returned by currents back under the continents where they are granitized and restored to the sialic crust. The Pacific margin suggests active shearing of the ocean floor beneath the continents, but where the continents have been drifted along with the sima the coasts are of more stable. "Atlantic", type.

Dietz' model appears to provide a promising mechanism to account for the epeirogenic changes that form the subject of this paper. It is tentatively proposed that at the close of Cretaceous time the continents had a much lesser relief and were rather more extensive than at present; they had substantially attained a position of dynamic equilibrium following fragmentation and dispersion by convection currents in the mantle. Subsequent history has consisted essentially of continued stretching of the ocean floor, thinning the basalt layer, and continued thickening and consequent uplift of the continents due to the transfer beneath them of sialic matter, derived partly from clastic detritus but mainly from the erosion of the base of the continental margins by currents moving toward the continental interiors. These margins have foundered as a consequence of isostatic adjustment. Accepting Flint's (1957) estimate of an increase in average continental relief from less than 1000 to 2500 ft, it follows, from Woollard's (1959) calculation that a change of 1 km in surface elevation corresponds to a change of 6.8 km in crustal thickness, that the sialic crust has thickened on average in Upper Tertiary and Quaternary times by over 3 km.

These changes have probably been effected in a series of pulses of intense activity. There has been in addition much local movement expressed both in the continents and oceans by a certain degree of differential uplift and subsidence, frequently located at least in the former, at the same sites. Under the continents the most significant process effecting such movements could have been the lateral transfer of sial. Under the oceans various processes may have contributed, such as the interaction of irregular eddies in the convection system, vulcanism, and even phase or compositional changes across the Mohorovičić Discontinuity.

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NOTE ADDED IN PROOF

Since this paper was written the author has come across a fascinating article on the East Pacific Rise by Menard (1960), which is highly relevant to the present enquiry. Menard suggests that the differing characteristics of the major oceanic ridges are related to different stages of development controlled by the growth and decay of convection cells in the mantle. For example, the East Pacific Rise has features suggesting it is younger than the Mid-Atlantic Ridge. This leads the present author to propose the following tentative hypothesis as a basis for discussion:

During the Mesozoic the growth of a major convection cell in the mantle caused the widening of the Atlantic and the growth of the Mid-Atlantic Ridge. Cretaceous uplift of this ridge, together with the Mid-Pacific mountains and perhaps the Pacific-Antarctic Ridge, resulted in a major displacement of sea water over the continents. Subsequent Tertiary decay of the convection cells has led to significant oceanic subsidence, reflected in a major regression of water from the continents. The regression has been only partially countered by phases of uplift over the vast area of the youthful East Pacific Rise, with, in consequence, periodic transgressions over the continental margins.

Whether or not these ideas prove acceptable in some form, it is hoped that they may stimulate investigation into the relationship between the global tangential movements that are the concern of students of continental drift and the radial movements that form the subject of this paper.

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