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REMARKS ON THE GENESIS OF FLINTS

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ABSTRACT. Ideas on the origin of flints have varied widely. Flints may have been formed by several different processes. For the flints typically found in the chalk, the syn-sedimentary replacement theory, pene-contemporaneous with the deposition of the chalk, has largely replaced the older diagenetic replacement theory. The finding in flints of extremely well preserved microfossils, still formed of organic material, even pointed to an almost unbelievably swift replacement. Palynological studies, by underlining the extreme toughness of these microfossils, and chromatographic analyses of macrofossils, by showing that organic material is widely present in common fossils, has lessened this difficulty.

No flint has yet been encountered forming at the present time. This is not surprising as flint should form in an environment hardly represented at present, namely, a warm, shallow sea, without terrigenous sedimentation, with a calcareous bottom but temporarily lacking even calcareous deposition. Most localities suitable for flint formation were obviously drowned by post-glacial eustatic rise of sea level.

INTRODUCTION

Flints. composed of crypto-crystalline quartz, are common in many formations. Their form is extremely variable, as is, to all appearance, their genesis. I shall therefore restrict these remarks to the flints of a very irregular form. each flint being built up individually by the fusing of a number of separate nodules of silicification. Such flints are typically found, for instance, in definite layers in the Upper Cretaceous of Europe. These flints, the "silex de la Craie", or the "Kreidefeuersteine", are associated with the chalk facies of the Cretaceous, the "Craie tuffeuse" or "Tuffkreide".

Well-rounded flints. also found in the chalk, may or may not have the same origin as the flints of irregular form. In some cases they are seen to be derived from irregular flints by erosion and abrasion, becoming re-deposited in the chalk somewhat higher up in the series. These questions are not further considered here. Nor do these remarks cover, for instance, the flints found in the limestone series of the Lower Carboniferous of western Europe (Cayeux, 1929). Their genesis may be quite similar to the flints of the chalk, but their more regular general form may well be due to later recrystallization in the Variscan geosyncline or during the Variscan orogeny.

I wish to restrict these remarks to the flints as they were when first formed by metasomatic recrystallization of limestone, and not take into account any later influences. My concern is with those flints which one would call "primary", were it not that their origin is already of a secondary nature.

THE DIAGENETIC THEORY

That the flints of the chalk are a secondary product. formed by metasomatic recrystallization of the original limestone, is proven by the many silicified fossils found in the flint, and by the fossils only partly silicified, partly within a flint nodule and partly still in the surrounding chalk.

Although there is no doubt as to the secondary nature of the flints, different views are possible as to the time of silicification.

Originally. the silicification was classed as a diagenetic process. taking place very slowly during the time between the formation of the chalk series and the present, a process taking many millions of years. Evidence for the circulation of vadose waters carrying a surplus of SiO_2 in the limestone environment of the chalk series is found in the deposits of crypto-crystalline quartz—resembling flint in all but its outer form and its position—on diaclases (joints) in the chalk.

There is, I think, no doubt about the origin during a much later period, of these flatwalled, thin, even sheets of "flint". These "Feuersteinvorhänge" or "flint-curtains" follow diaclases which cut through all or most of the complete series of the chalk. But convincing evidence has accumulated in later years that the normal, irregular flints of the chalk, found in separate layers in the series, were formed in another way.

CAYEUX AND PENE = CONTEMPORANEOUS FORMATION OF FLINTS

A major attack on the theory of later, diagenetic formation of flints was launched by Cayeux (1897). A great many detailed observations on the "silex de la Craie" in northern France had supplied him with numerous examples of flints having developed almost directly after the formation of the layer of chalk in which they are found. Flints, for instance, broken up into sharp-edged fragments by intraformational erosion and re-deposited in the next layer of chalk, prove that silicification was already complete, before the formation of that next layer of chalk. Consequently, Cayeux regarded the origin of the flints of the chalk as syn-sedimentary or pene-contemporaneous, and not due to a much later process.

It follows that the apparently tranquil and regular series of the chalk is formed by a succession of rather different types of environmental circumstances, rhythmically following each other. There is first the period of chalk sedimentation, characterized by an open, well-aerated sea floor, without terrigeneous sedimentary supply, resulting in the formation of a rather pure organo-detrital limestone. Then follows a period of non-deposition with local superficial silicification of the newly formed limestone, proceeding from a great number of separate silicification nuclei. Thereafter, the "normal" environment of the chalk sea may have been re-established, or a longer period of non-deposition, or even a period of erosion, may have followed, before the next advent of the chalk sea.

It is from the latter periods, which are not necessarily developed in every small-scale chalk sea rhythm, that Cayeux's observations on an early formation of flints are derived.

Cayeux's ideas on the pene-contemporaneous origin of the chalk flints were rather revolutionary. They even led him to the thesis that the formation of the chalk flints and related formations were due to nonactualistic processes: the "causes anciennes en géologie" (Cayeux, 1941). Although these conclusions were disputed by Lafitte (1949) and myself (Rutten, 1949), I wish to stress that only the non-actualistic conclusions were questioned. The factual observations of Cayeux stand as before, and have been reinforced by later work.

IRREGULARITIES IN THE CHALK SERIES

I think that everyone who has studied chalk series in detail will, in due time, have found similar indications of flints, eroded, reworked or abraded.

and redeposited in a chalk layer immediately following that from which the flints were taken. In every such case, the flints behave as tough bodies, with typical conchoidal fracture. They were already silicified, whereas no subsequent silicification has taken place in their secondary place of sedimentation.

As a matter of fact, detailed bed for bed analysis of a great number of series, not only of the chalk, but also of comparable facies, has brought to light that the "tranquility" of these series is entirely misleading. On the contrary, they are the result of several different environments, subsequently changing and following each other in a rhythmic pattern. Moreover, they are cut by larger irregularities, leading to periods of non-deposition, to hardgrounds or to actual erosion and emersion. All these features are normally included in these apparently tranquil and concordant series.

The genesis of the flints of the chalk accordingly takes its place within the series of rather variable periods of sedimentation and non-sedimentation, which made up the chalk. It is, in a sense, comparable to the dolomitization of a limestone series. There also we have learned to distinguish between a later wholesale post-sedimentary dolomitization and the pene-contemporaneous dolomitization of specific beds of limestone.

TIME OF SILICIFICATION

Geologically speaking, the local silicification of the limestone of the chalk into the flints, although secondary, consequently is an early process. As it follows immediately upon sedimentation, it is called syn-sedimentary or pene-contemporaneous.

As to the number of years this process has actually taken, we have no definite clue. The "geologically" short period between the formation of one layer of chalk and the next younger one may well be counted in thousands of years.

A series of limestone beds is not formed by a constant process. In that case there would be no beds or bedding planes, but only a massive limestone. Every bedding plane is the expression of an interruption in, or a change of, the sedimentation process. Every bedding plane forms an indication that for a given time other conditions held sway than those leading to limestone sedimentation. Every bedding plane might in fact represent a diastem, a period of non-deposition. But there are very few facts that allow an absolute, or even a relative measure for the time taken up by the formation of the bed and that of the bedding plane.

Sonder (1956) recently stressed the importance of the bedding-plane diastems in an apparently continuous series. With characteristic impetuousness, he arrives at more or less precise figures for the duration of the periods in which beds and bedding planes were formed. Unfortunately, these figures are based on estimates of speed of sedimentation which are far from exact. They are not worthy of consideration, beyond the fact that they too, indicate the possibility of thousand-year periods for the formation of single diastems.

It is of importance to realize the extremely long time, as counted in years, involved in a process like the formation of flints, which geologically is an early process. The silicification of the newly formed chalk on the sea floor, during a period of non-deposition, or even perhaps of partial emersion, is pretty sure to be under the influence of biochemical processes. The latter are regulated by yearly or even seasonal changes. Consequently, thousand-year periods, available for the formation of bedding-plane diastems or for the formation of flints, before the sedimentation of the next higher chalk layer begins, are very long indeed from a biochemical standpoint, although they may be short-lived and pene-contemporaneous, when viewed from the angle of the stratigraphical column.

THE MICROFOSSILS

Although no further indications as to the time needed by the silicification process could be gained from the macroscopic examination of the flints, evidence for a very quick silicification was provided by some of the microfossils. These indications came from the studies of unicellular microfossils, mainly by O. Wetzel and G. Deflandre.

Wetzel (1933 and many other papers) recognized that unicellular microorganisms were fossilized in the flints as organic substances. They were not silicified. Although these fossils are resistant against strong acids and bases, this seems to indicate almost immediate fossilization in the siliceous material.

This opinion was emphasized even more strongly by Deflandre (for instance 1936), who not only described *Hystrichosphaeridae* with beautifully preserved pseudopodia, but also *Flagellata* with flagellae of a thinness and length that is difficult to obtain by the most careful preparation of recent material.

Moreover Deflandre (1935a) succeeded in coloring the microfossils contained in flints by normal biological coloring agents, such as ruthenium red, eosine, fuchsine, methylene blue and dahlia violet. The fact that some coloring agents, such as hemalum and fast green had no effect on the microfossils, might of course be due to a degradation of the organic material during fossilization, but it can also be explained by some influence of the surrounding SiO_2.

Since it is our experience that, in general, organic material is destroyed rather quickly, say in a matter of years, these observations point to an almost immediate fossilization of the micro-organisms in the flints. From a normal, geological early process of syn-sedimentary character, the silicification became something like a spontaneous process. It seemed as if it occurred almost spontaneously, *à la minute*, following directly upon the sedimentation of the limestone in the chalk.

Newer observations have taught us, however, not to place too much emphasis on the organic nature of the microfossils in the flints. They come from two different sources, viz. from palynology and from a general chromatographic study of normal fossils.

In palynological studies of Tertiary deposits in Venezuela, Kuyl, Muller and Waterbolk (1955), for instance, reported that *Hystrichosphaeridae* occur not only in lignites but in shales as well. They belong to the most resistant of microfossils. They have not only withstood fossilization in normal sediments, but also the subsequent ordeal of the preparation of palynological samples.

The latter includes boiling with HF, HNO_3, HCl, KOH and a mixture of H_2SO_4 and acetic acid, all in rather strong concentrations.

These palynological studies confirm the fact, already stressed by O. Wetzel (1933), that these micro-organisms, although consisting of organic material, are remarkably resistant.

Modern paper chromatography, on the other hand has shown that "normal" fossils, such as pelecypod shells, often retain protein and its amino-acid degradation products over long periods in geological history (Abelson, 1956).

It follows that the coloring of microfossils contained in flints by Deflandre likewise is not conclusive as to a very sudden, *à la minute* silicification and fossilisation.

THE SILICIFICATION PROCESS

From these newer facts we may conclude that the genesis of chalk flints is a more or less normal, early geological feature. The flints are of a secondary nature, and were formed syn-sedimentarily by a silicification following the deposition of the organo-detrital limestone of the chalk.

Although we may arrive at a definite idea of the time at which the silicification took place, and while we can indicate, in a general way, what its environment was, we have no idea about the details of the subject. The theory, put forward to explain the immediate, *à la minute* silicification, still is very attractive. This surmises temporary, partial emersion, in quiet environment, leading to a period of a warm, very shallow sea, in which *Silicospongiae* flourished. Locally, a silica gel would have formed on the sea floor, which reacted with the underlying limestone of the chalk, leading to local metasomatic replacement of $CaCO_3$ by SiO_2.

Siliceous sponges, with their small needles, which fall apart when the animal dies, may be very propitious in forming a temporary overabundance of silica on the sea floor, but other organisms, micro-organisms in particular, may be responsible for this phenomenon also (Douvillé, 1932).

Newell et al. (1953) also use the silica of siliceous sponge needles to explain both the formation of siliceous nodules and the de-silification and calcification of the sponge needles. There are, however, some differences between their nodules and the flints of the chalk. The flints are related to diastems and are formed on top of an underlying layer of chalk. Moreover, as Cayeux demonstrated in many cases, they were formed before the next layer of chalk was deposited. Also, no large amounts of sponge needles are found in the chalk, or they may even be absent altogether.

The process proposed by Newell et al. operates in the uppermost limestone layers, the process proposed by Cayeux and Douvillé on the surface of a chalk layer, during a temporary exuberance of Silicospongiae. These two processes presumably are not exclusive, but may have operated each in its own area and environment. Newell et al. postulated solutions of sufficient concentration for the chemical reactions of desilicification and calcification of the sponge needles and the formation of siliceous nodules. Cayeux stressed the influence of microbes in replacement reactions taking place in warm and shallow seas.

Personally, I believe Cayeux made a very strong point in stressing biochemical activities in these replacement processes. In that way a silica gel could form in surroundings where no purely chemical silicification is possible. Microbiologists often criticize their fellow scientists as apt to forget the immense importance of microbes in all matters of life and decay, and geologists are probably the worst offenders. If our present civilization were fossilized, one would, perhaps, be able to recognize a dairy from a bakery, a brewery or a "*cave coopérative*" in wine-growing France, but never would the microbes underlying the different processes characterizing these industries be visible. The importance of microbiology for sedimentation processes in warm, shallow seas in a calcareous environment, has for instance recently been stressed by Nesteroff (1956).

Cayeux's theory is to be sure no more than an *ad hoc* hypothesis. There is no detailed knowledge of the processes leading to the genesis of flints, because, as yet, we know no part of the seven seas where flint is forming now.

This is, of course, an argument for the old theory of formation of flint through later diagenetic processes, while it is against the ideas put forward in this paper, of pene-contemporaneous silicification, geologically synchronous with sedimentation, and occurring on the sea floor during periods of altered environmental conditions.

GENESIS OF FLINTS AND ACTUALISM

"Show me a single spot on earth", the diehards of the diagenetic theory will say, "where flints are formed now, and I will be convinced". Unfortunately, we are, as yet, unable to show them such a locality.

This is a difficulty encountered not only in the genesis of flints. We meet it again, at least partly, in other processes which are of a syn-sedimentary character. Bed-for-bed silicification or dolomitization of limestones and the formation of iron oolites are comparable cases. This difficulty led Cayeux to abandon actualism (uniformitarianism) and to suppose the existence of "*causes anciennes*".

Personally, I have always held that it is not necessary to abandon actualism, if only two factors are considered which are, I think, of great importance. First, actualism does not mean that processes now active have always been as active in geological history. Also, processes, possible now, but relatively inactive, might have been far more active formerly.

In this context, it should always be borne in mind, that we live in a very peculiar period of the Earth's history, which is characterized by being both interglacial and post-orogenic. In contrast, the more normal periods of the Earth's history—and the formation of the chalk during the Upper Cretaceous is very typical indeed—are characterized by being non-glacial and a-tectonic (Rutten, 1953).

Secondly, it is a well known fact that marine geology is still in its infancy. Notwithstanding the many cruises made, there is hardly any area of the seven seas where the environment provided by the seasonal changes of the seawater, and its interrelation with fauna and flora, has been studied over more than a decade.

As to the first point, the difference between our present-day shallow seas and those, for instance, of the Upper Cretaceous must be very great indeed. All former shallow seas, where sedimentation had built the sea floor up to effective erosion through wave action, were drowned, together with the adjoining continental lowlands, through the post-glacial eustatic rise in sea level. Our "shelf seas" consequently do not form a geologic unity, nor is the "neritic zone" a biological unity. The shelf sea is composed of deeper elements of former littoral and "neritic" character and higher elements of former continental character. Biologically, the shelf seas consist of a supra-neritic zone of some 40 m to 50 m deep, in which vigorous life is possible and which forms a biological unit. To this supra-neritic zone is added a deeper zone, only because of the convenience of the 100-fathom line. The lower boundary of our present "neritic" zone is indicated by the amount of the post-glacial eustatic rise of the sea level. It has nothing to do with biology, and it does not constitute a definite boundary of an ecological zone.

Moreover, we are now in a period of strong continental erosion, following upon the uplift of many areas of our continents, which in turn is probably the direct consequence of the Alpine orogeny. Tectonically speaking, our present day circumstances are comparable to those of the Old Red and the New Red periods, with extensive continental masses, and terrigene sedimentation strongly prevalent. This is in total contrast with, for instance, the Upper Cretaceous, when—at least in Europe—tectonic unrest was at its minimum, and calcareous sedimentation, without terrigenous supply, prevailed.

We must imagine the Upper Cretaceous chalk sea as a very wide, shallow, well aerated sea, bordered by a base-levelled continent, from which no terrigenous sedimentary supply was derived. It was not a shelf sea in our present-day sense of the word, and "epicontinental sea" would perhaps be the best word for it. The climate was tropical. The shallow sea was so wide, that tidal influences were not felt, but an occasional hurricane might have been important in churning up the soft, not yet consolidated, calcareous detritus.

Small rhythmic crustal movements of cyclothem or even sub-cyclothem scale, had great influence in regulating the succession of sedimentation periods and their alternation with periods of non-sedimentation, of erosion or emersion. During the latter periods, the circumstances were repeatedly favorable for local development of a silica surplus on the sea floor, and subsequent superficial silicification of the limestone and the formation of flints.

HOW TO LOOK FOR RECENT FLINT FORMATION

Where, we may ask, will we find at present the conditions of the chalk sea during the Upper Cretaceous? The search is limited to areas with a tropical or subtropical climate; areas where recent sedimentation has offset the post-glacial eustatic rise of the sea level; and areas where there is no appreciable terrigenous sedimentary supply.

Truly, there are, from the Bahama Bank to various bays of the Red Sea, along the northern coasts of Australia, and in atolls of the Coral Sea, local areas, where calcareous sedimentation has offset the post-glacial rise of the sea level. In these scattered places we may locally study the formation of coral reefs, of rocks of the reef-complex, or of calcareous oolites.

These areas are, however, characterized by the deposits belonging to a period of vigorous calcareous organic or organo-detrital sedimentation. It will be only through a freak of the environmental conditions that we will find at present an area of non-deposition, within an environment of calcareous sedimentation, which is still so near to the surface, that silica-secreting biochemical reactions may flourish there. The correlation of the formation of the chalk flints to periods of non-sedimentation is in itself almost prohibitive to the finding of such an area at present.

All normal areas of non-deposition have been covered by 80 m of sea water during the last 10,000 years of the Holocene. So we must search for the chance of an abnormal area. This might be, for instance, a spot where crustal movements have offset the post-glacial drowning. Or where, some short while ago, calcareous sedimentation has outgrown the drowning.

The chance of finding such an abnormal area is not very great. But even if it is comparable to the needle in the haystack, a search can be conducted on better lines, if one knows what to look for. In the case of present-day flint formation, this must consequently be an area of non-deposition in an environment of a warm, shallow sea with calcareous sedimentation, without terrigenous sedimentary supply. Personally I am fully confident that the exploration teams of marine geology will find in due course such an example of present-day flint formation.

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