Discontinuity Surfaces in Limestones

By

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ABSTRACT.—Discontinuity surfaces (referred to in the literature also as surfaces, pits, and zones of corrosion and as emersion surfaces) indicate non-deposition and breaks in the sequence. These structures have been described from many different areas in Europe and North America in limestones ranging from Ordovician to early Tertiary. Morphology and stratigraphic occurrence and significance of selected discontinuity surfaces are briefly discussed. The origin of these surfaces has been ascribed to either subaerial exposure or exclusively submarine agencies.

Many discontinuity surfaces show clear evidence of having been lithified prior to the deposition of the overlying beds. Submarine lithification of carbonate sediments at or close to the surface by calcite or aragonite cement is not known, and no theoretical explanation can at present be given for its occurrence in a comparable scale at depths less than 150 m below sea bottom. In tropical and subtropical latitudes the subaerially exposed carbonate sediments often show a considerable degree of lithification. This and the stratigraphic evidence, particularly the connection of certain discontinuity surfaces with undoubted land surfaces, make it highly probable that the surfaces which can be shown to have been lithified before the deposition of overlying beds have been subaerially exposed and represent emersion surfaces. Discontinuity surfaces occur in areas with an extensive level bottom of the ancient sea. Their areal distribution in a palaeogeographic sense indicates mostly islands and peninsulae. The extremely low altitude of these land areas and the probable closeness of the base level of karst erosion to the land surface have prevented the formation of karst phenomena. There scarcely exists any soil upon comparable Recent areas. The discontinuity surfaces evidently obtained their final shape during and after the subsequent submersion by possible corrosion in the intertidal zone, scouring and polishing effect of calcarenitic grains in suspension, boring and encrusting organisms, and by other agencies. A small-scale Recent discontinuity surface is briefly described.

Breaks in a carbonate sequence without any lithologic evidence of a break may be due to submarine non-deposition, erosion, or both. It is suggested that such breaks may have been formed also by subaerial exposure in a cool climate and without lithification of the emerged sediment.

Distinct surfaces with or without a stain can be formed also in exclusively submarine environment. Some of them indicate breaks and hence represent discontinuity surfaces. The need for detailed descriptions of the morphology of discontinuity surfaces is stressed.

Introduction

A discontinuity ("corrosion") surface in limestone is a distinct surface which indicates a break in the sequence. It mostly shows signs of etching, boring activities of organisms, or of both.

A deeply pitted discontinuity surface was figured already by KUPFFER (1876) from the Ontikan (upper Lower Ordovician) limestones of Estonia. He suggested that the pits had probably been formed by organic agencies. CHAMBERLIN (1882, pp. 413, 421) briefly described a discontinuity surface from the Champlainian (Middle Ordovician) of Wisconsin and was evidently the first to realize that it indicates a break in the sequence. The first detailed descriptions and good figures were given by ANDERSSON (1896), particularly of the contact surface between the Cambrian and Ordovician limestones of Sweden and also of similar surfaces from the lower Ontikan limestones. He coined the term corrosion pits, a term which was used also by HEDSTRÖM (1896*a*, 1896*b*) and LAMANSKY (1905) who described further examples of discontinuity surfaces from Ontikan limestones of Sweden, Estonia, and Ingermanland. Similar structures were treated from the Champlainian of Minnesota by SARDESON (1898, 1914), who termed them corrosion zones, by MUNIER-CHALMAS (1897) from the boundary between Danian and Palaeocene of France, and by HEIM (1908, 1910*a*, 1910*b*, 1913, 1916, etc.) from the Jurassic, Cretaceous, and early Tertiary limestones of Switzerland. HEIM introduced the term discontinuity surface for these structures. Further literature, where the discontinuity surfaces are described, discussed, or mentioned, is fairly voluminous and not perspicuous, the references concerning these surfaces being usually hidden in stratigraphical descriptions. The published information about these structures comes almost exclusively from certain areas: Ordovician and Silurian of Balto-Scandia, Devonian of European Russia (recent summary by HECKER, 1960), Champlainian (Middle Ordovician) of the Upper Mississippi Valley (for recent summaries, see PROKOPOVICH, 1955, and WEISS, 1954, 1958), and Jurassic, Cretaceous, and early Tertiary of the Alps (for summary, see HEIM, 1924) and France (good descriptions by KLÜPFEL, 1917, and ELLENBERGER, 1947). The most detailed studies hitherto published on stratigraphic significance and morphology of discontinuity surfaces are those of ORVIKU (1940, 1960), and deal with the lithology of the Ontikan and Lower Viruan limestones of Estonia.

When studying the literature about discontinuity surfaces, it soon becomes evident that, in discussions about the origin of these structures within a certain area, no or very little consideration has been given to the relevant information from many other areas. In fact, the existence of similar structures in most of the other areas seems in many cases to have been unknown. The discussions about the origin of the discontinuity surfaces have therefore often become somewhat one-sided. This paper is intended to summarize most of the published information about these structures, to discuss their origin, and to arouse a still greater interest in their detailed morphological studies. The writer's first-hand acquaintance with discontinuity surfaces is restricted to their Ordovician representatives in Estonia, Sweden, and in some localities of NE Iowa, SE Minnesota, and the Arbuckle Mountains of Oklahoma. Much relevant information, scattered as it is in numerous stratigraphic papers, has certainly escaped the writer's attention.

The author has had the privilege of getting some of his early experience of discontinuity surfaces under the inspiring direction of Professor KARL ORVIKU (formerly at Tartu University, now in Tallinn). He has profited from numerous discussions with Professor PER THORSLUND (Uppsala University) and from his eminent knowledge of these structures. Visits to the localities displaying discontinuity surfaces in Iowa, Minnesota, and Oklahoma were made possible by the most generous guidance of Dr. W. M.

FURNISH (State University of Iowa), Mr. O. KARKLINS and Mr. G. F. WEBERS (University of Minnesota), and Dr. W. E. HAM (Geological Survey of Oklahoma), respectively. Of particular value has been the possibility of getting some first-hand knowledge about the Recent and subfossil features of carbonate deposition along the Florida Keys and in the Florida Bay, and the author is deeply indebted to Dr. ROBERT N. GINSBURG (Shell Oil Co., Coral Gables) for his help and generous guidance through parts of these areas.

Occurrence, Morphology, and Stratigraphic Significance of Discontinuity Surfaces

The published information about discontinuity surfaces mostly deals with the stratigraphic occurrence and significance of these structures. Good illustrations and detailed morphological descriptions are few. For this reason it is sometimes difficult to know what are the real characters of the surfaces designated as emersion, corrosion, or discontinuity surfaces. The general knowledge of these structures seems, with the exception of some countries, to be slight among stratigraphers, and in many areas these surfaces have probably not been recognized as such. Below some well-known discontinuity surfaces are briefly described in order to give an idea of the main morphological features of these structures.

The first adequately described and well-illustrated discontinuity surface is the contact between the Cambrian and Ordovician limestones of Västergötland and Närke, Sweden (ANDERSSON, 1896, Pl. VII; THORSLUND, 1937, Fig. 6; KAUTSKY, 1949, Fig. 5). This can be regarded as a classical example of such structures. The Upper Cambrian sequence of Sweden consists of bituminous shale (alum shale) with large lenses (concretions) of dark bituminous limestone (stinkstone; Swedish "orsten"). The Ontikan (upper Lower Ordovician) glauconitic limestone rests in some places upon the shale and in others upon the stinkstone. In the latter case the contact surface is uneven (Fig. 1 *A*), deeply pitted (Fig. 1 *B*), rarely dovetailed (Fig. 1 *C*; ANDERSSON, 1896, Pl. VII, Fig. 1), or quite smooth (ANDERSSON, 1896, Fig. 3, Wåmb). The pits within the stinkstone are filled with limestone from the overlying basal Ontikan bed. The limestone inside the pits is often richer in glauconite than the beds above; in addition phosphatized grains of various size and pieces of stinkstone occur in the pits or in the overlying limestone bed or beds (Fig. 1 *A*, *C*; ANDERSSON, 1896, Pl. VIII, fig. 1; THORSLUND, 1937, Fig. 6). Locally the accumulation of pebbles gives the basal Ontikan bed or beds a conglomeratic appearance. Large pebbles have been shown to contain Upper Cambrian trilobites belonging to the zone underlying the discontinuity surface (ANDERSSON, 1896, p. 191; THORSLUND, 1937, p. 159). The contact surface is usually covered by a thin film of glauconite. The uppermost 2 to 6 cm of the stinkstone are mostly bleached, conspicuously paler than below, the lower boundary of the bleached zone being as a rule sharp and even (Fig. 1; ANDERSSON, 1896, Pl. VII, fig. 2). The bleaching process

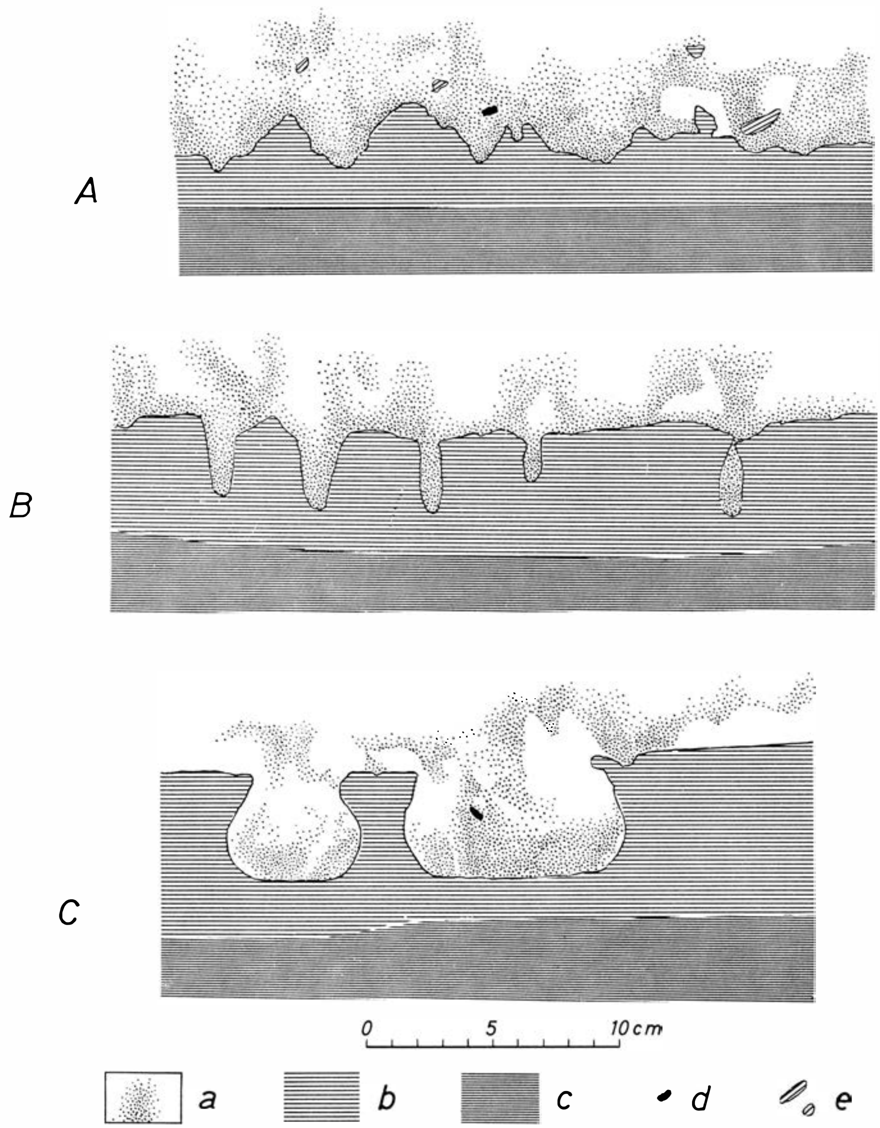

Fig. 1. Discontinuity surface at the boundary between Upper Cambrian stinkstone (*b* and *c*) and Ordovician glauconitic limestone (*a*). *A*, Hynneberg, Närke. *B*, Stora Stolan, N. Billingen, Västergötland. *C*, Lanna, Närke. Signs: *a*, Ordovician glauconitic limestone; *b* and *c*, bleached and unbleached Upper Cambrian stinkstone, respectively; *d*, phosphatic pebbles; *e*, pebbles of bleached stinkstone. After samples in the Museum of the Palaeontological Institute of Uppsala.

had evidently ceased prior to the formation of the pits (ANDERSSON, 1896, p. 189). When the Ordovician limestone rests upon the Upper Cambrian alum shale, the contact surface is without pits and generally even. However, the upper 2 to 4 cm of the bituminous shale are often bleached in the same manner as the stinkstone below the boundary. The bleaching is, in part at least, obviously due to oxidation of bituminous substance (HEDSTRÖM, 1896*b*; WESTERGÅRD 1928), though no quantitative data are available.

The above discontinuity surface marks an extensive break in the sequence. The extent of the break varies in different districts and in different parts of a district. The boundary between the Cambrian and Ordovician is characterized by a break in the whole of Balto-Scandia, with the exception of Scania, where the break, if present, is very inconsiderable, and of the Oslo district, where the sequence is quite complete. The pitted surface described is developed at that level only on condition that the Ordovician limestone is in contact with the Upper Cambrian stinkstone as in Västergötland, Närke, and the Autochthonous of Jämtland, along a distance of c. 550 km. There the break usually comprises the whole Tremadocian Subseries, or the Tremadocian Subseries and the lowermost Ontikan (Arenigian) zones, as well as the uppermost part of the Upper Cambrian Series (for details, see TJERNVIK, 1956). When the rocks on either side of the boundary are shales, no macrolithologic evidence of a break has been observed, and the existence of a hiatus can be proved only upon the basis of faunal succession. When the boundary lies within a sequence of sandstones as in Estonia and Ingermanland, the hiatus comprises at least most of the Upper and Middle Cambrian Series, and the boundary is defined in places by conglomeratic structures or small-scale erosional features, in some places however, only by a slight lithological change at a more or less plane and often ill-defined surface (MÜÜRISEPP, 1958).

Similar discontinuity surfaces, though mostly not as conspicuous, are numerous in the Tremadocian and the Lower Ontikan limestone sequence of Sweden (for figures, see ANDERSSON, 1896, p. 186; HEDSTRÖM, 1896, Figs. 1–2; THORSLUND, 1937, Figs. 3, 6; BOHLIN, 1955, Fig. 1; HADDING, 1958, Figs. 2, 4; for occurrence in different sections, see TJERNVIK, 1956), and in the Ontikan and Lower Viruan sequence of Estonia (ORVIKU, 1927, 1940, 1960). The general morphology of these surfaces resembles that of the contact surface between the Cambrian and Ordovician, but (owing to the lack or paucity of bituminous matter) no bleached zone is developed. Owing to a concentration of iron or phosphatic compounds, or both a narrow zone immediately below the surface differs in colour from the rest of the rock (zone of impregnation, ORVIKU, 1940). Phosphatic, pyritic, haematitic, and limonitic (goethitic) impregnations are known. In some cases a thin, finely laminated limonitic or pyritic crust underlies the surface (cf. ORVIKU, 1940 and STAUFFER, 1925, respectively). ORVIKU (1960) distinguishes between plane discontinuity surfaces and those with an uneven relief. The more or less plane surfaces (ORVIKU, 1940, Pl. XVII, XVIII, Fig. 1; 1960, Figs. 4–6) usually have a narrow zone of impregnation and are pierced by borings of *Balanoglossites* and, especially, of *Trypanites* types (MÄGDEFRAU, 1932; MÜLLER, 1956); some have amphora-like borings (ORVIKU, 1960, Figs. 4, 9; HECKER, 1960, Pl. II, figs. 1, 2). In the discontinuity surfaces with uneven relief (ORVIKU, 1940, Pl. XV; 1960, Figs.

1–3, 11, 13) borings tend to be rarer and are often of an irregular shape. The former type has probably been formed mainly by hydrodynamic agencies and the latter type by hydrochemical influences (ORVIKU, 1960). One of the types can merge into the other along the extension of a discontinuity surface. The bed overlying the discontinuity surface contains locally pebbles derived from the rock below the surface. A more elaborated type of conglomeratic structure has been described by HEDSTRÖM (1896*b*) from the lowermost part of the Ordovician limestone sequence in the SW part of the Siljan district. There the Ontikan limestone is separated from the Archaean basement by a thin bed of glauconitic rock only. Between the closely spaced discontinuity surfaces of the lowermost limestone beds lie pebbles of granite, porphyry, and Jotnian sandstone.

All these surfaces mark breaks of varying duration in the deposition. Their stratigraphic significance can be illustrated by E–W sections from Ingermanland (Leningrad district) to western Estonia (LAMANSKY, 1905; ORVIKU, 1940, 1960). The Ontikan and lowermost Viruan sequence is fairly complete in the east and becomes increasingly incomplete towards the west. Members, parts of zones, and then entire substages wedge out in a westerly direction, the location of breaks being marked by discontinuity surfaces which appear and become more distinct and elaborated in this direction (ORVIKU, 1940, Table II and III; 1960, figs. 7 and 12). At that time there existed west and south-west of the NW Estonian mainland an island or a peninsula (so-called Central Baltic uplift; cf. THORSLUND, 1960, Fig. 3, lower right) the marginal area of which is known from borings upon Gotland and Gotska Sandö. There the uppermost Ontikan limestone rests directly upon the Lower Cambrian sandstone and exposes numerous discontinuity surfaces at its base (THORSLUND, 1958, Fig. 2). In NW Estonia the incomplete and thin succession of the Kunda Stage (the upper stage of the Ontika Subseries) grades into a calcareous quartz sandstone, the Pakri Formation. The terrigenous sand material of this formation is probably derived from the Lower Cambrian still poorly lithified sandstone, then subaerially exposed in the Central Baltic uplift. In places the limestone underlying the calcareous sandstone, or the main part of the calcareous sandstone itself, or both are traversed by vertical joints, which occasionally continue parallel to the bedding, and hollowed out by cavities, some of them fairly large, filled with calcareous sandstone from above (ÖPIK, 1927, Fig. 15; ORVIKU, 1960, Figs. 16–19). These structures evidently represent karst phenomena (like those figured by PARKER & COOKE, 1944, Fig. 4) and are formed in subaerial conditions.

Some of these discontinuity surfaces are of great extent. The characteristic surface with amphora-like borings (figured already by KUPFFER, 1876; ORVIKU, 1960, Fig. 4, 5, 9; HECKER, 1960, Pl. II, fig. 1), separating the Billingen and Volkhov Stages (Päite and Saka Members; $B_{I}\gamma$ and $B_{II}\alpha$ as defined by JAANUSSON, 1960), can be followed from Ingermanland to westernmost Estonia, a distance of about 400 km (LAMANSKY, 1905). A surface at the same level in at least some places of Sweden has an identical morphology. Several other surfaces are well defined along northern Estonia, e.g. the discontinuity surface at the base of the Kunda Stage and that at the base of the Aseri Stage. The lower substage ($B_{III}\alpha$) of the Kunda Stage wedges out already in western Ingermanland and is not developed in northern Estonia. The corresponding break is marked along its entire extension by a distinct discontinuity surface (LAMANSKY, 1905; ORVIKU, 1960). At Narva in eastern Estonia the Aseri Stage (the lowermost stage of the Viru Series or Middle Ordovician) is 3.35 m thick and becomes gradually thinner by the wedging-out first of the lower member and then of the middle member; it is represented on the island of Osmussaar in western Estonia by only 10 cm of calcareous oolitic sandstone corresponding to the top of the stage in eastern Estonia. The breaks at the base of and within the stage are indicated by well-defined discontinuity surfaces (for details, see ORVIKU, 1940).

A similar wedging-out of a moderately thick limestone sequence bordered by discontinuity surfaces occurs also in the lower substage of the Viruan Idavere Stage (JAANUSSON, 1945; RÕÕMUSOKS, 1957), but the detailed morphology of the discontinuity surfaces has not been described yet. The basal discontinuity surface of this substage can be identified also in borings on Gotland and Gotska Sandö (unpublished evidence).

Discontinuity surfaces occur likewise in the Silurian limestones of Estonia (AALOE, 1960), but no detailed descriptions are available.

The Devonian discontinuity surfaces in the Main Devonian Field of Russia (HECKER, 1960) resemble the plane type of those in the Ordovician of Balto-Scandia. The surface is pierced by numerous narrow borings of the *Trypanites* type (HECKER, 1960, Pl. V, fig. 3). In addition, the surfaces exhibit traces of a rich epifauna, consisting of tabulates, pelmatozoans, and brachiopods (*Crania*, *Irboskites*) which encrust the plane surface of discontinuity. The surfaces occur at many different levels (for their occurrence in time and space, see HECKER, 1960, Fig. 9).

The stratigraphic significance and occurrence of discontinuity surfaces in the Jurassic and Cretaceous of Switzerland (e.g. HEIM, 1910*b*, S. 271, 1913, Fig. 95) is, at least in part, very similar to those in the Ordovician of Estonia. However, the detailed morphology of the surfaces is seldom described, and hence it is difficult to form an opinion of the real character of some of the surfaces. Much of the relevant information can be found in different papers by HEIM (1910*b*, pp. 36–39; 1913, p. 363; 1916, pp. 554–558; cf. also 1924). As an example the discontinuity between the Lower Cretaceous Albian and Aptian Stages in eastern Swiss Alps (the basal discontinuity of HEIM, 1913, p. 361) can be cited. The discontinuity surface is described as completely smooth except in some places, where the surface is pierced by pits made by boring lamellibranchs (HEIM, 1913, p. 362), or shows solution phenomena, like fissures or deep pits (HEIM, 1910*a*, Figs. 68, 73; 1910*b*, Fig. 4).

Surfaces termed emersion surfaces and described by KLÜPFEL (1917) from the Jurassic limestones of Lorraine are quite plane. Protruding parts of colonies of corals that had formed small elevations upon the sea-bottom have been removed along the surface "as by a razor" (KLÜPFEL, 1917, p. 99, footnote 1). The surfaces are often encrusted by numerous oysters (op. cit., Pl. III, fig. 2, Pl. IV, fig. 2) and pierced by vertical pits made by boring lamellibranchs and other organisms (op. cit., Pl. IV, fig. 2). Occasionally the surfaces coincide with those of ripple-marks covered by oysters and traversed by borings; locally they occur in groups separated by thin beds that show cross-bedding. The beds overlying the surfaces are mostly clayey and often contain pebbles derived from the limestone underlying the surface. Occasionally the pebbles are covered by a thin film of ferric oxide and by encrusting oysters, serpulids, solitary corals, bryozoans, and other organisms; they also contain numerous borings. Characteristic of many surfaces is the concentration of phosphate and pyrite at, and immediately below the surface; in this case a considerable phosphatization occurs also in beds overlying the discontinuity surface. For further particulars, see KLÜPFEL, 1917. In the Jurassic sequence of Lorraine he recognized 30 to 40 of these discontinuity surfaces.

The surfaces with borings described by MÄGDEFRAU (1932) from the Middle Triassic limestone of the Saale Valley, Germany, very much resemble the discontinuity surfaces treated by KLÜPFEL.

The contact surface between Danien and Palaeocene in the Paris Basin has been described in great detail by ELLENBERGER (1945, 1947). The plane surface of limestone is pierced by numerous borings, previously interpreted as produced by the roots of land plants (MUNIER-CHALMAS, 1897). Many different types of borings are distinguished and compared with known borings in recent seas. Some of the borings attain a length of more than one metre. The contact surface with the above characteristics has a wide extension in the Paris Basin. A discontinuity surface has been recorded at the same level also in Denmark (ROSENKRANTZ, 1924, Fig. 2; GRY, 1935, p. 26, Fig. 4), where it forms an unevenly undulating surface with numerous cavities and holes presumably produced by boring organisms (GRY, 1935). The bed above the surface often contains rolled fossils derived from Danian limestone. In the northern Alps of Switzerland the Tertiary succession overlies, with a break at the base, paradisconformably various Jurassic and Cretaceous divisions (cf. HEIM, 1908, Fig. 18). Locally the basal Tertiary beds contain pebbles derived from underlying limestone. Mostly, and especially when overlain by an Eocene glauconitic limestone ("Assiliengrünsand"), the contact surface is smooth (HEIM, 1908, Pl. VI, fig. 30), evidently without a stain, only seldom with small 2 to 4 cm deep pits (HEIM, 1908, p. 17), and without pebbles in the overlying bed.

Origin of Discontinuity Surfaces

The selected examples of discontinuity surfaces, briefly described in the preceding chapter, resemble each other in their general morphology and stratigraphic significance. This suggests that their formation is due to the same main agencies. On comparison of discontinuity surfaces from different periods certain differences in the details of morphology are noticeable which obviously reflect differences in the development of boring and encrusting organisms. The known Ordovician discontinuity surfaces usually show only one or two types of borings in the same surface; the length of the borings rarely exceeds 15 cm. Encrusting organisms (bryozoans, pelmatozoan roots) have been reported only on pebbles derived from eroded discontinuity surfaces (SARDESON, 1898, p. 319). The Devonian discontinuity surfaces carry locally an encrusting fauna, rich in individuals though poor in species at least in the Main Devonian field of Russia (HECKER, 1960). The borings seem to be more complicated than in the Ordovician, but no detailed descriptions are yet available. On Jurassic and later surfaces oysters form a dominant component in the encrusting fauna; many different types of borings may occur in the same surface (ELLENBERGER, 1947), some of them exceeding 1.5 m in length. However, the morphological details of a greater number of discontinuity surfaces have to be described before safe generalizations can be made. The importance of comparative studies of signs of the hard-bottom fauna from different periods has been stressed by HECKER (1960).

Two different main explanations have been proposed for the origin of the particular discontinuity surfaces dealt with by the respective authors:

(1) The surfaces have emerged (CHAMBERLIN, 1882; HEDSTRÖM, 1896*a*, *b*; MUNIER-CHALMAS, 1897; LAMANSKY, 1905; KLÜPFEL, 1917; ROSENKRANTZ, 1924; WESTERGÅRD, 1928; GRY, 1935; THORSLUND, 1937; KAUTSKY, 1953; WEISS, 1958; HESSLAND, 1959).

(2) They have been formed exclusively by submarine agencies (ANDERSSON, 1896, 1897; SARDESON, 1898, 1914; STAUFFER, 1925; PETTIJOHN, 1926; ORVIKU, 1940, 1960; ELLENBERGER, 1945, 1947; PROKOPOVICH, 1955; WEISS, 1957; HADDING, 1958; HECKER, 1960).

HEIM (1910*a*, *b*, 1913, 1916, 1924) evidently regards the surfaces which show borings, solution phenomena, or which are associated with conglomeratic structures as having emerged, whereas the surfaces which are described as smooth are interpreted as due to submarine agencies (non-sedimentation (omission in HEIM) and submarine solution and erosion (ablution in HEIM)).

The proponents of the idea that discontinuity surfaces represent emersion surfaces usually stress the great extension of some of the surfaces, the often considerable hiatus defined by them, and the gradual and mostly regular wedging out of parts of a succession in a certain direction with discontinuity surfaces as indicators of breaks. These features as well as the occasional presence of associated conglomeratic structures are considered to indicate subaerial exposure of the discontinuity surfaces. The probable impossibility of submarine lithification of soft carbonate sediments has been hinted at by HEDSTRÖM (1896*b*, p. 595, footnote 1).

The opponents of that view have considered the absence of real beach deposits, conspicuous traces of erosion, karst phenomena, dessiccation fissures, and traces of soil as evidence against subaerial exposure of the surface. Pyritic stain and "worm tubes" have been regarded as indications of submarine origin.

However, none of the above evidence seems to be, in itself, of decisive importance in favour of either the first or the second interpretation. The present writer, coming from a school where the submarine origin of the discontinuity surfaces was regarded almost as a fact to a school where the subaerial origin of these surfaces was considered nearly proved, has felt intensely the inadequateness of evidence adduced in support of both the above explanations.

Most writers who have dealt with discontinuity surfaces agree that the rock below the surface must have been lithified to some extent before the deposition of beds overlying the surface has begun (e.g. ANDERSSON, 1896; HEDSTRÖM, 1896*b*; SARDESON, 1898; LAMANSKY, 1905; ROSENKRANTZ, 1924; WESTERGÅRD, 1928; GRY, 1935; THORSLUND, 1937; ORVIKU, 1940, 1960; ELLENBERGER, 1945, 1947; HESSLAND, 1959; HECKER, 1960). The evidences indicating such lithification are several. (1) The deeply pitted, uneven surfaces often show overhanging portions (e.g. ANDERSSON, 1896, Pl. VII, fig. 1; ORVIKU, 1940, Pl. XVII, fig. 2, 1960, Fig. 5; WEISS, 1954, Fig. 2) which in soft calcareous sand or sand-mixed calcareous mud could not possibly stand without collapsing. (2) The occasional presence of pebbles derived from rock underlying the surface or from the surface itself. In this connection attention ought to be drawn to interesting observations by HOLM (1895, p. 608, footnote) in a certain bed of the grey *Vaginatum* Limestone (the Hunderum Substage) of northernmost Öland. In this bed worn siphonal tubes of endoceratids are secondarily accumulated forming a kind of conglomerate in which the pebble fraction consists mainly of isolated siphonal tubes. Many of the latter show narrow borings (of *Trypanites* type), which pierce not only the shell, but also the limestone and coarsely crystalline calcite filling the tubes. The siphonal tubes have been deposited, partly filled with sediment, eroded, and redeposited, and not only the sediment filling the tubes had become lithified before the boring organisms attacked the siphonal tubes, but also the calcium carbonate filling the voids within the tubes. Recent studies have shown that the described conglomeratic bed occurs in close connection with a well-developed, almost smooth discontinuity surface with numerous, mostly narrow borings of the *Trypanites* type. (3) In many cases it can conclusively be shown that the holes in the surface made by organisms are borings and not burrows. In Jurassic and later discontinuity surfaces some of the borings closely resemble those made by Recent animals (ELLENBERGER, 1948). (4) The presence of encrusting oysters and other organisms show the surface to have been firm enough for encrusting forms. (5) Many discontinuity surfaces exhibit probable solution phenomena. But in the case of deeply pitted surfaces the structures interpreted as solution pits could not possibly have originated by corrosion of the surface of a soft calcareous sand or mud.

The circumstance that a discontinuity surface has been lithified prior to the deposition of the overlying bed may give the best clue for the correct understanding of the origin of the surface. No undisputable evidence of a submarine lithification[1], on a comparable scale, by calcium carbonate cement of a Recent calcareous sand or mud at or close to the surface is known, nor does it seem possible to deduce the physico-chemical process that would cause such lithification. The information pertinent to submarine compaction and lithification of sediments has recently been analysed by HAMILTON (1959). According to him, the pressure-induced lithification of a calcareous ooze would probably begin at depths from 150 to 700 m below the bottom of the sea. So if the hardened condition of the discontinuity surface is explained by submarine erosion of the unlithified sediment down to a depth where it had become hardened (HECKER, 1960), much greater thicknesses ought to have been removed than have possibly been available for submarine erosion in areas with discontinuity surfaces.

It is, on the other hand, a well-known fact that in tropical and subtropical regions marine carbonate sediments which are, or have been, subaerially exposed are often indurated to a varying degree. The lithification may take place during relatively short time by a precipitation of interstitial calcium carbonate under the influence of increased temperatures as in beach-rock deposits (GINSBURG, 1953, 1957, pp. 95–96; EMERY, TRACEY & LADD, 1954, pp. 44–47).

If the discontinuity surfaces are emersion surfaces, an explanation must be found for the absence of karst phenomena and terrestrial soil as they occur upon most Recent land surfaces with carbonate bed-rock. The problem can perhaps be best clarified by an attempt at visualizing what could be expected to happen, when a bottom of a sea like that of ancient seas with discontinuity surfaces were to emerge and be again submerged.

A conspicuous feature of the bottom of such seas is the almost complete flatness. In the Balto-Scandian area outside the Caledonides the sub-Cambrian peneplain is known to be in itself fairly plane, and the small irregularities in the relief to have been levelled off by the subsequent deposition of the Cambrian, particularly the Lower Cambrian, sediments. With some minor, tectonically controlled exceptions the bottom of the Ordovician sea had no noticeable relief.

[1] Recent submarine occurrences of lithified carbonate rocks are known from many places, but none of these rocks has yet been proved to have become lithified at or close to the bottom of the sea. A Recent carbonate crust has been reported from some places on the bottom of the Caspian sea (SOLOVIEV, 1956), but the possibility does not seem to be excluded that it has been formed under subaerial conditions during an interglacial age.

The latter is true also of the bottom of the Devonian, Jurassic, Cretaceous, and early Tertiary seas in areas with discontinuity surfaces. No counterpart to such flatness of the bottom over such large areas is found in Recent epicontinental seas, and this makes the understanding of the relative importance of various geologic processes acting in such ancient areas in submarine as well as subaerial conditions fairly difficult.

If the water was shallow, a slight regression from such a level plain of carbonate sediments caused emersion of a flat land area with probably an irregular coast-line, and here and there of islands which rose only slightly above the sea-level and which may have been flooded during storms (LAMANSKY, 1905, p. 188). The details of coast-line were probably changing from time to time, since the change in the direction of the prevailing winds may have flooded large areas and laid dry others. On account of the negligible slope of the beach real beach deposits were rare. In tropical and subtropical climates at least the superficial portion of the carbonate sediment on the land became lithified by the precipitation of interstitial calcium carbonate. Erosion of the surface began, but was fairly ineffective on account of the very gently sloping land surface and the small vertical distance between this surface and the base level of erosion. Most of the erosion probably took place as sheet erosion and corrosion. Most of the solution was obviously caused by rain water. Drainage of meteoric waters took place along the surface, since in such a landscape the base level of karst erosion could scarcely be much below the surface. However, in some parts of the land area with greater vertical distance between the surface and the ground water level solution may have formed large pits and cavities which were used for the drainage of meteoric waters (some discontinuity surfaces merge into those with karst phenomena).

Solution of calcium carbonate by meteoric water and, possibly, organic agencies produced a residual soil which consisted of the terrigenous component of the limestone (mostly clay substances) and of those authigenic minerals which are poorly soluble in weak acids (pyrite, ferric oxide, hydrous ferric oxide, glauconite, probably some phosphatic compounds, etc.). The layer of residual soil was probably not thick. Andros Island, which in many respects resembles an island within an ancient sea with discontinuity surfaces, has hardly any soil cover (NEWELL, RIGBY, WHITEMAN & BRADLEY, 1951, p. 10). However, the altitude of the island still considerably exceeds that of the land areas emerged from the above ancient seas.

When the land area in question was again submerged, the residual soil ought to have been removed to a great extent. There are several examples showing the effectiveness of beach erosion for the removal of loose material from a hard limestone plane. One of the examples is that described by SUMMERSON (1959) from the boundary between Silurian and Devonian of Central Ohio. In a part of a quarry the contact surface shows conspicuous karst phenomena and is overlain by red clay and iron-cemented sandstone and clean, white, wellsorted quartz sandstone, altogether 0.5–0.6 m thick (SUMMERSON, 1959, fig. 1). The whole unit pinches out within a distance of 35 m, the karst phenomena disappear, and the boundary surface becomes "a smooth, sharp, wavy line" (SUMMERSON, op. cit., p. 425), of which, unfortunately, no detailed description is provided. The extent of the hiatus at the boundary varies in different parts of Ohio and may comprise more than a series. It seems probable that the portion of the Silurian surface showing karst phenomena was situated in a slight depression which protected the surface and the soil from reworking, washing, and erosion (SUMMERSON, op. cit., p. 428). In the nearby areas all traces of weathering and soil were removed by erosion which produced a smooth wavy surface. A detailed description of this surface would be of great interest.

Abrasion on an extremely gently sloping beach consisting of moderately indurated calcium carbonate sediments produces, *a priori*, rarely conglomeratic structures. Pleistocene and Recent lithified marine carbonate rocks known to the present writer have retained much of the original porosity and can be fairly easily disintegrated by abrasion. For this reason much of the unevenness of the surface produced by subaerial erosion and corrosion may have been levelled off by even slight abrasion, resulting, in extreme cases, in an almost completely smooth surface. In the intertidal zone corrosion may have had a continued activity (EMERY, 1946; FAIRBRIDGE, 1948; REVELLE & EMERY, 1957).

When submerged, the surface of the abraded or washed limestone plain was attacked by boring animals and, in suitable places, encrusted by organisms. Through these processes the emersion surface was given its final shape.

The submersion was likely to be followed by a period of non-deposition. Upon the hard and smooth limestone floor the subsequently deposited loose carbonate sediment could easily be moved back and forth by currents and storms and be in part transported into deeper parts of the basin or to places with a tranquil water. However, owing to the general flatness of the bottom of the sea the period of non-deposition, if present at all, may often have been insignificant in a sea of the type described.

As mentioned above, the extensive and almost complete flatness of the bottom of ancient seas with discontinuity surfaces has no closely comparable counterpart in the Recent seas with carbonate deposition. However, also Recent and subfossil discontinuity surfaces do exist, though their continuous spatial extension is much inferior to that of many ancient discontinuity surfaces. The best example known to the writer is the contact surface between the Pleistocene Key Largo Limestone and the Recent carbonate sediments in some places along the eastern coast of the Florida Keys. The Key Largo Formation consists of coral reef limestone of Sangamon Interglacial Age (cf. PARKER & COOKE, 1944), and has been subaerially exposed and lithified during the last (Wisconsin) Ice Age, when the sea-level was much lower than at present. Along the eastern coast of Florida Keys the submerged area of the reef limestone is covered by a blanket of Recent calcarenite of varying thickness. Locally the contact surface is almost completely plane over considerable areas; coral heads have been truncated along the surface and lie at the same plane as the sediment filling the spaces between the corals. No solution phenomena could be observed, but the surface of the limestone between the corals shows traces of probable borings. The base of the recent calcarenite does not seem to contain any pebbles, and there is no trace of a soil. The surface layer of the Key Largo limestone does not show any stain, and if the Recent calcarenites were lithified and the contact region exposed in a quarry, a superficial examination of the sequence would show a sudden change in facies at the contact. Only the abruptly truncated corals and possible traces of organic borings would indicate emersion, erosion, and a break in the sequence comparable to the Wisconsin Ice Stage. Similar smooth planes of erosion of lithified limestone, bare or covered by a thin blanket of calcareous sand or mud, have been described by FAIRBRIDGE (1948) from Recent reef flats. He pointed out that calcareous sand in suspension is a very powerful erosive scouring agent that smoothes and polishes the limestone on the reef flat.

Most of the discontinuity surfaces are easily recognizable on account of the contrasting colour of the zone of impregnation. ORVIKU (1940) found that in the cases where the zone is stained by iron compounds, particularly limonitic substances, the lower boundary of the zone is mostly independent from the relief of the surface; the rock around terminal parts of the borings, in particular, is very faintly stained or unstained. On the other hand, the generally much narrower zone of phosphatic stain is usually of constant width and tends to follow the irregularities of the surface. ORVIKU concluded that the limonitic zone of impregnation is formed before the surface got its final shape, whereas the phosphatic stain was formed contemporaneously with, or later than, the final relief of the surface. According to him, the formation of a laminated limonitic crust took place after the borings were completed. The present writer has noticed that the iron compound forming the stain is mostly identical with that prevailing in the bed adjacent to the surface; if the latter is pyritiferous, the stain also tends to be pyritic, if limonitic, limonite also forms the impregnation, etc. An exception is the common presence of a limonitic (goethitic) stain within an otherwise haematitic limestone (HEDSTRÖM, 1896, Figs. 1, 2) though also haematitic stain below the surface is known in limestones, where the prevailing iron compound is haematite. STAUFFER (1925) and PETTIJOHN (1926) suggested that the pyritic stain was formed on the surface under anaerobic conditions, but with a view to the above the possibility must be kept in mind that the original stain was ferric, and that the reduction may have taken place subsequently through influence of the chemical milieu of the interstitial water of the overlying deposits (cf. also WEISS, 1958, p. 487). The writer's experience shows that the intensity of the stain may have some relation not only to the duration of the submarine exposure of the surface but also to the content of iron and phosphatic

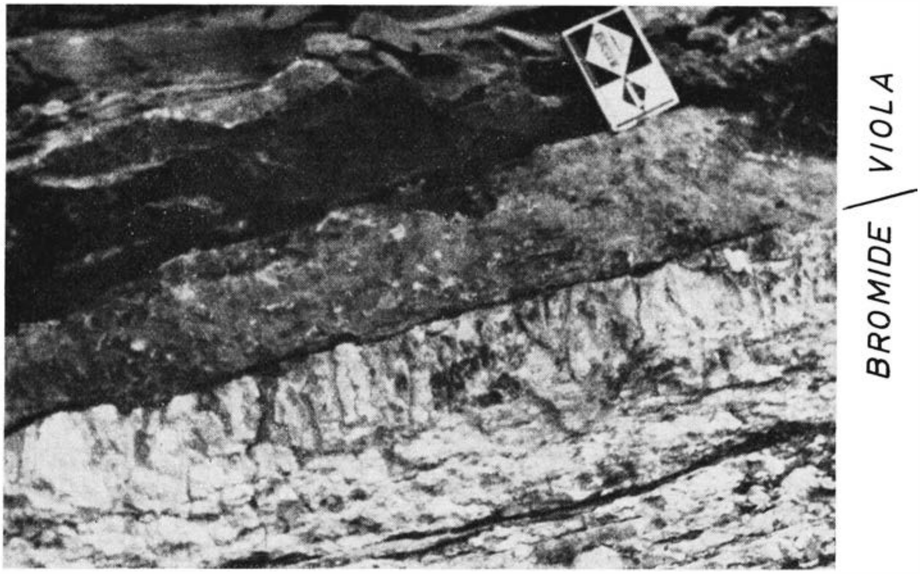

Fig. 2. Discontinuity surface, with borings, at the boundary between the Bromide Formation and Viola Limestone. Arbuckle Mountains, Oklahoma, road section at Oklahoma State Highway 99, 3 km S of Fittstown. Length of the match-box 5 cm. Photo V. Jaanusson 1959.

compounds in the beds underlying the discontinuity surface. The surface formed upon rocks comparatively rich in iron or phosphatic substance, or both, show a distinct stain, whereas those upon limestones poor in these compounds are faintly stained or show no zone of impregnation at all. As an example of the latter type the contact between the Champlainian Bromide Formation and Viola Limestone in Oklahoma can be mentioned. Presence of a break between these formations has been suggested, for palaeontological reasons, by Cooper (1956, p. 121). In the section of Oklahoma State Highway 99, 3 km S of Fittstown, the sharp boundary between these formations is developed as a distinct discontinuity surface with numerous vertical borings of the *Trypanites* type (Fig. 2). No obvious stain can be observed. Compared with the Balto-Scandian limestones, the rock is very poor in iron as well as in phosphorus. The absence of a stain on the contact surface between the Key Largo Limestone and the Recent calcarenite may depend upon the same reason, the Key Largo Limestone being an almost pure carbonate.

Details of the mode of formation of the zone of impregnation are still not clear. The stain seems to be formed under submarine conditions, while the lithified surface was bare. There are indications that the source of the various substances forming the stain is related to the residue of the limestone that is insoluble or poorly soluble in weak acids. Further discussion of this subject would, at the present state of our knowledge, be too speculative.

The evidence derived from the stratigraphic occurrence of the discontinuity surfaces does not seem to be quite decisive, since breaks due to non-deposition, erosion, or both occur also under submarine conditions. However, it can be proved in several instances that a discontinuity surface has a close connection with a surface the terrestrial nature of which nobody has questioned. The discontinuity surface at the boundary between the Cambrian and Ordovician in Närke and Västergötland can be regarded as a direct continuation of the same boundary upon Baltic islands and in Estonia, where the Ordovician beds overlie Lower Cambrian or lowermost Middle Cambrian sandstone. The wedging-out of the Ontikan limestones of Estonia in a westerly direction has an obvious relation to the Central Baltic uplift on the western flank of which the uppermost Ontikan limestone is known to overlie the Lower Cambrian sandstone. Some discontinuity surfaces are known to continue into surfaces with karst phenomena. If such discontinuity surfaces have been land surfaces, their areal distribution in a palaeogeographic sense indicates in many cases islands and peninsulae, *a priori* of an extremely low altitude, emerged from a sea with an almost quite plane bottom. With a view to this the rarity of what are considered as characteristic subaerial phenomena in connection with discontinuity surfaces is readily understandable.

The interpretation of the discontinuity surfaces as due exclusively to submarine agencies leaves some questions unanswered. (1) The process of an extensive submarine lithification of a carbonate sediment at or close to the bottom of the sea. (2) Submarine corrosion in case of a normal composition of sea-water. In tropical and subtropical climates normal sea-water at the surface is supersaturated with respect to calcium carbonate, though the figures reported for the degree of supersaturation vary (for recent summary, see HARVEY, 1957; cf. also REVELLE & EMERY, 1957 and GARRELS, THOMPSON & SIEVER, 1959). The supersaturation with respect to calcium carbonate in ancient seas with discontinuity surfaces is made probable by the occasional occurrence of thick sequences of calcilutites in close proximity to these surfaces. In case of normal sea-water a submarine solution of calcium carbonate would be improbable except at considerable depth or in relatively cold water. Solution may occur in isolated basins, where the composition of the sea-water is not normal, as in brackish waters or under conditions of stagnation. The increase in the duration of the break marked by a discontinuity surface is accompanied in several cases by clear sedimentological indications showing an increase in the turbulence of the water (like the increase in the size of oöids and in the abundance and size of quartz grains; cf. ORVIKU, 1940). It has been suggested that such phenomena could be explained by currents (PROKOPOVICH, 1955) and in particular by cold currents (HADDING, 1958). However, it would be difficult to apply the idea of a cold current as dissolving medium to discontinuity surfaces which can be shown to be closely connected with the undoubted land surfaces mentioned above, i.e. formed in a shallow sea close to the coast. In the direction off the coast the solution phenomena become rarer and disappear, the sequence becomes complete, and lithologic evidence indicates a more tranquil environment. With respect to the supposed exclusively submarine corrosion the above seems like a reversed order of conditions. Cold currents restricted just to areas close to the coast would constitute quite exceptional phenomena in a sea with a practically level bottom.

The degree of lithification of a subaerially exposed carbonate sediment can vary depending upon the duration of subaerial exposure, the consistence of the sediment, and other factors. Discontinuity surfaces seem also to show different degrees of lithification prior to the deposition of the overlying bed (HEDSTRÖM, 1896*b*, p. 611; LAMANSKY, 1905; ORVIKU, 1940). Stained or unstained surfaces, some of them indicating a break and hence representing discontinuity surfaces, are formed also under exclusively submarine conditions, and the distinction of these from subaerially exposed surfaces, especially when the latter have been only slightly lithified, is not easy. Such discontinuity surfaces can be formed, when submarine erosion exposes deposits which are firmly compacted by former sediment cover (cf. e. g. ERICSON, EWING, WOLLIN & HEEZEN, 1961, pp. 235–240). It may be difficult to prove whether the firm condition of a surface before the deposition of the overlying beds has been due to compaction or to lithification. Truncation of a shell along a surface does not necessarily mean corrosion. Protruding parts of a shell partly imbedded in the sediment may, in case of a low sedimentation intensity, be completely destroyed by organisms.

There also exist breaks in the carbonate sequence without any distinct lithologic indication of a break at that level. A good example is the contact between the Silurian and Devonian in the Arbuckle Mountains of Oklahoma (AMSDEN, 1957, 1960), and other examples are known, even in Sweden in Ordovician limestones, where breaks are otherwise indicated by discontinuity surfaces (unpublished material). Such breaks may be due to either of two possibilities: (1) submarine non-deposition combined with, or independent of submarine erosion, and (2) emersion, but without lithification of the emerged sediments. Lithification of subaerially exposed carbonate sediments occurs in many tropical and subtropical areas. In temperate and cool climates, however, subaerial induration of calcareous sand seems to be rare. Late Glacial and post-Glacial accumulations of marine coquina and calcarenite have been subaerially exposed in Scandinavia, Svalbard, and other areas by the isostatic land elevation. Most of these deposits are still quite loose, though the writer is of the opinion that they would have been conspicuously hardened, had they been formed in tropical regions. The poor lithification of subaerially exposed carbonate sediments in regions with cool climate evidently depends on the higher content of carbon dioxide in the sea-water and on the lower intensity of evaporation by insolation. A transgression upon a plane land area with still loose carbonate sediments below a thin layer of soil, if present, would scarcely leave any well-defined lithologic boundary in the sequence. However, the factors controlling lithification in different sediments and in various environments are still poorly known, and generalizations in this respect are premature.

The term discontinuity surface ("Diskontinuitätsfläche") was coined by HEIM for distinct surfaces marking a break without regard to the cause of the break. The corresponding English term is surface of disconformity. However, the term discontinuity surface is preferred here, because it has become to designate a particular, well-defined type of surface of disconformity. It has been used, also by HEIM, for surfaces indicating a break in the limestone sequence. For the surfaces which can be proved to have emerged the term emersion surface can be used. The term corrosion surface or corrosion zone suggests a definite mode of formation of the surface, and as such surfaces are rarely formed exclusively by corrosion, the use of this term may give rise to misunderstandings. In any case this term can scarcely be used for ORVIKU's plane type of discontinuity surfaces.

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