THE CONDITIONS OF BLACK SHALE DEPOSITION AS ILLUSTRATED BY THE KUPFERSCHIEFER AND LIAS OF GERMANY.

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Stratigraphers do not agree as to the conditions under which the black bituminous shales so often met with in American Paleozoic marine deposits were laid down. Among the more striking of such formations may be mentioned the Quebec, Martinsburg, Collingwood, Utica, Maquoketa, Genesee-Portage, Ohio, Chattanooga, and Caney, formations ranging from the Ordovician to the Pennsylvanian. To aid in the interpretation of such black shales, the writer presents herewith the main results set forth by Professor J. F. Pompeckj, of the University of Tübingen, in a publication that will not be of wide distribution in America.[1] The following is a decided condensation and in part a free translation of his exhaustive paper, which is replete with bibliographic references.

The Kupferschiefer of Germany are of Middle Permian age, and occur near the base of the Zechstein, the time of marine invasion over the previous continental series known as the Rotliegende. In general, the bituminous dark shales occur above the basal Zechstein conglomerate and below the Zechstein dolomite, and occupy an area of at least 60,000 square kilometers in middle and western North Germany. The average thickness of the copper shales over wide areas is about 30 inches, but varies from nothing to a maximum and exceptional local thickness of 35 feet. However, in many places there are no black shales and then the equivalent deposits, or the basal strata of the invading Zechstein, may be conglomerates, sands, shaly limestones, or dolomites. In other words, the black bituminous shales do not prevail everywhere, and the same is true of the metal sulphides.

[1] "Das Meer des Kupferschiefers," Branca-Festschrift, 1914, pp. 444–494.

The copper-bearing shales usually succeed the basal conglomerates or sands and finally become gradually more and more calcareous, passing upward into the normal Zechstein dolomite of wider distribution. The latter has an abundant though monotonous fauna indicative of peculiar marine conditions and not much like that of the Tethyian mediterranean to the south, which is of normal sea environment. The paleogeography indicates an inland sea, bounded by continuous land, in the north by Fennoskandia across to England, thence south to France and Belgium, and east over South Germany to Bohemia. In the east only were there limited connections with the Russian and Arctic Zechstein sea. The previous orogenic movements resulting in the Paleozoic Alps of central Europe had been greatly reduced, so that the streams flowing into this Permian sea were sluggish and delivered only the finest of muds and solution materials, while those flowing out of regions of igneous rocks were charged in addition with copper, zinc, and silver.

The Kupferschiefer are fissile, tough, dark to black, highly bituminous (6 to 20 per cent.), clay shales with considerable calcareous material that increases in amount upward (locally to 45 per cent.). Copper sulphides variable in quantity and nature are present, and because of this ore the strata have been mined in Germany for seven hundred years. Under the microscope the shale is seen to be made up of finest clay substance colored yellow-brown to black by bitumen. Throughout the clay there are scattered, layered, or aggregated in the form of thinnest lenses varying amounts of tiny crystals of calcite and needle-like splinters of quartz. Black coaly dust is also more or less abundant and especially among the clay particles.

The flora and fauna of the Kupferschiefer are small and at best do not include more than 1 land stegocephalian, 2 land reptiles, 17 fishes (5 selachians, 1 crossopterygian, the rest ganoids) with structures indicating forms that lived on or near the bottom of the waters, 1 nautilid, 1 gastropod, 1 scaphopod, 10 bivalves, 3 bryozoa (Fenestellidæ), 5 brachiopods, 1 problematic starfish, and 11 species of land plants. This assemblage is brought together from many localities and the species of fishes are usually based on single specimens, indicating that the biota is not a natural assemblage, but is made up of land and marine forms plus fishes, most of which appear to be of fresh water habitat. The only common fossils are the ganoid *Palæoniscus freieslebeni, Lingula credneri, "Asterias" bituminosa* (problematic), and the small bivalves *Nucula beyrichi* and *Bakewellia antiqua* (sometimes in colonies). In other words, the life consists of land-derived forms (3 vertebrates and 11 plants), fishes (5 probably marine and certainly bottom-feeding, and 12 apparently of river origin), and 22 marine invertebrates all but one of which are forms living on the bottom of the sea, attached to it or to floating objects. While the invertebrates indicate plainly that the copper shales were laid down in the sea, the great scarcity of fossils shows that the forms recovered are in the main not in their normal habitat. It appears that only 3 species (the invertebrates cited) were able to adapt themselves to the peculiar conditions of the copper-depositing seas. Not a single scavenging animal is found, and the fact that so many fishes (17 species) were present as food (*Palæoniscus freieslebeni* is often more or less decomposed by sulphur bacteria) indicates that the bottom had no scavengers and that it was not a favorable place for any kind of life.

Pompeckj has carefully studied the fishes, and as all or most of them are carnivorous (some are shell-feeders) the question is raised: On what could they have fed, since there was so little bottom life? He admits that there may have been present an abundance of soft-bodied and shell-less invertebrates on which they preyed, but finally concludes that it is much more correct to assume that most of the fishes (at least 12 species) were drifted into the sea from the rivers. If they also lived in the sea, it must have been in the oxygenated surface waters or the shallow shore regions. On the other hand, the invertebrates present indicate that nearly all of them fed on microscopic plants and animals (no ostracods are present, however) and it is perfectly natural to assume that the surface and sun-lit waters abounded in a varied plankton, as do the seas and oceans of today. It was this world of minute forms, the plankton, that rained into the depths, feeding the sparse brachiopod and molluscan life and the common sulphur bacteria.

Moreover, it is the abundant surface plankton that in all probability has furnished most of the bituminous matter, assisted further by the land-derived fishes, while the coaly substance has resulted from the land plants. Along the shores, in the oxygenated waters, there probably also was an abundance of sea-weeds and among them doubtless lived most of the invertebrates preserved in the Kupferschiefer. The marine plants are broken up by the storms, and the water currents plus the undertow generated by the waves and tides drag this material into deeper waters, where it is slowly rotted and further altered by the sulphur bacteria. There results a foul bottom, free of oxygen, and reeking with carbonic acid and sulphuretted hydrogen gas. The chemical reactions set up here (diagenesis) result in the deposition of the metal sulphides (copper, zinc, silver) and the bituminous alteration products.

The paleogeography, as stated above, indicates an inland and almost land-locked sea. Into such a basin the currents generated in the oceanic areas can at best enter but little, and that such did not enter in any marked degree is seen in the almost complete absence of floating and swimming invertebrates. As for the general physical conditions, Walther thinks of stagnant waters, with marine swamps; Kayser of quiet bays of inland seas with foul bottoms; and Dosz of stagnant places like the present bays around the island of Oesel, where the bottoms are rich in iron sulphide deposits, the healing or medicinal muds. Pompeckj, however, finds more or less valid objections to all of these suggestions, and thinks the best present analogue to be the Black Sea, whose physical and organic conditions are now well understood through the work of Andrussow and Lebedintzew. In other words, the Kupferschiefer sea is "a fossil Black Sea" in nearly all its characteristics except depth.

With regard to the conditions of the Black Sea, it is an inland, relic sea, which was once a part of the Tethyian mediterranean. Its greatest length is about 715 miles and its maximum width 380 miles (making its area 170,000 square miles), and it attains 7,360 feet in depth. Flowing into it are many rivers, among the largest of which are the Danube, the Dnieper, and the Don. Its only outlet of surface water is through the strait and over the barrier of the Bosporus into the Sea of Marmora and thence through the strait of Dardanelles into the Ægean Sea and the Mediterranean. A compensating but smaller inflow of salt water (salinity 3 per cent.)

occurs at greater depths. The shores are high and bold on the northeast, east, and southwest, and flat on the north and northwest.

Andrussow[2] has described the physical and bionomic conditions of the Black Sea as follows: Beyond the shallow marginal waters of 600 feet depth there is no bottom-living life (benthos), while in the surficial fresher waters down to about 750 feet there is a more or less great abundance of floating, usually microscopic, open-sea forms (plankton) and the larger, free-swimming life (nekton), collectively also spoken of as the pelagic biota. This upper layer of freshened water and its peculiar life conditions are brought about by the enclosed nature of the deep basin, the inflowing of immense quantities of less dense fresh water that remains at the surface or is there evaporated, and a deep-seated, partially compensating current of salt water from the Sea of Marmora through the strait of Bosporus. It is estimated that it takes about 1,700 years to renew the entire salt-water content of the Black Sea.

Because of these differences between the lighter surface and the heavier bottom salt waters, there is no vertical streaming nor convection currents beyond 750 feet of depth, and therefore no replenishing of the deeper marine waters with the oxygen that is so necessary for the maintenance of benthonic life. At the depth of 600 feet, hydrogen sulphide begins to form (33 c.c. in 100 liters of water) and increases rapidly with the depth to 3,000 feet (570 c.c.) and then more slowly to the bottom of the sea. The formation of the H_2S is in the main due to the sulphur bacteria. Hand in hand with the increase of the H_2S goes the decrease of the sulphates in the sea water and the precipitation of the carbonates and iron sulphides.

That the aëration of marine waters, and also the generation of sulphuretted hydrogen may be better understood, a digression into the studies of oceanographers becomes necessary. The atmospheric gases, oxygen and nitrogen, are absorbed at the sea surface more abundantly in cold than in warm latitudes, and the quantity absorbed is again variable under varying pressures and chemical conditions of the water. This complex subject, too long to state here, may be

[2] "La Mer Noire," Guides des Excursions, VII^e Cong. Géol. Internat., St. Pétersbourg, 1897, Art. XXIX.

studied in Krümmel's "Handbuch der Ozeanographie," I., 1907, pages 292–317. Furthermore, the amount of oxygen is increased when there is an abundance of assimilating plants, as in the areas of the sea-weeds and diatoms. The gases are then distributed by the general water circulation to most parts of the oceans and even into the greatest depths. In general, there is an abundance of oxygen down to 350 feet, but in the tropics it is wanting in the greater depths of the shelf seas. The oxygen is consumed by the animals and by various hydro-chemical processes and consequently diminishes in quantity as it is carried down from the surface and over the bottom, but the quantity of nitrogen remains constant. Sir John Murray states further that in the streaming open ocean of today there is usually an abundance of oxygen even at the greatest depth, due to the sinking heavier and colder polar waters, but this is not the case in partially enclosed seas which are more or less cut off by barriers and where the water is said to be "stale," and in the deeper layers of which vertical circulation is restricted.

Similar stagnant conditions "prevail in several Norwegian 'threshold fjords,' or on a smaller scale in the oyster-'polls.' In such places the bottom is thickly covered with organic matter; a slimy black mud is formed, swarming with bacteria that produce sulphuretted hydrogen, which spreads through the water, combining with the oxygen to form various sulphates. This causes the oxygen to decrease and finally to disappear altogether, when the sulphuretted hydrogen begins to appear free in solution. It gradually spreads upwards, until the water is devoid of oxygen and contains free sulphuretted hydrogen, at a depth of only 100 fathoms in the Black Sea, and in the oyster-basins in autumn often at merely a couple of meters below the surface. In summer the 'bottom-water' of the oyster-'polls' lies stagnant, but in the course of the autumn and winter it is generally renewed by the supply of comparatively heavy water from without; then the sulphuretted hydrogen disappears and the oxygen returns, producing thus an annual change in the gaseous conditions of the deeper parts of the oyster-'polls.' In autumn the state of things may become critical for the oysters, which are suspended in baskets at a depth of 1½–2 meters; it happens occasionally that the animals all die at this time by suffocation through want of oxygen or by sulphur poisoning."[3]

Johnstone[4] states that "In some parts of the sea, as for instance in the 'dead grounds' of the [very shallow] Bay of Kiel, in some parts of the Black Sea, and perhaps in parts of some of the Norwegian fjords, where the water circulation is defective, and where there may be a deficiency of oxygen, very remarkable bacteria are to be found. These are the sulphur bacteria, the occurrence of which is not, however, confined to these habitats. In the places I have mentioned sulphuretted hydrogen is evolved from the decomposition of dead organic matter, and this sulphuretted hydrogen, to us a vilely smelling and poisonous gas, is utilized as food substance by the bacteria. Such a microbe as Beggiatoa takes in the SH_2 and oxidizes it so that the sulphur is deposited in the cells of the bacterial colony, and the hydrogen appears as water. This is the form of assimilation of the organisms. Then some of the sulphur thus resulting from the decomposition of the SH_2 is oxidized to sulphuric acid. This is the form of respiration of the organism. It requires some source of nitrogen for the formation of its living proteid and this it obtains from the minute quantities of nitrates and nitrites which exist in solution in the water in which it lives. But it requires very little nitrogen compound, for whereas a higher animal may require to oxidize some of the living nitrogenous tissue of its own body in order to obtain its energy, the sulphur bacterium oxidizes the sulphur stored in its cells as the result of the assimilation of the SH_2. Thus the proteid part of the cell is protected from waste, and the minimal quantity of nitrogenous food-stuff suffices."

Krümmel states that the troughs of the Baltic Sea renew their deeper water irregularly and periodically. In the Rügen and Bornholm troughs (about 325 feet deep) the renewal takes place at least once and more rarely twice each year, in the Danzig trough (about 325 feet deep) nearly every year, and in the deeps off Gotland and in the Gulf of Bothnia usually only after many years. All these troughs get the new deeper water from the western Belt Sea and more rarely also from the Öresund east of Denmark.

[3] Sir John Murray, "The Depths of the Ocean," 1912, pp. 257–258.

[4] "Conditions of Life in the Sea," 1909, p. 264.

To return to the Black Sea and its sediments, these are of three categories: (1) from the shore to about 120 feet occur the accumulations of sandy detritals; (2) from 120 to 600 feet is found a gray-blue sticky ooze, often replete with small fragile shells, mainly of Modiola; and (3) in the greater depths the bottom is covered with (*a*) a tough, sticky, black ooze, with much precipitation of iron sulphide, an abundance of diatoms and fragments of the youngest stages of bivalves, all of which organisms are from the plankton, and (*b*) the dark blue ooze poor in iron sulphide and richer in the finest-grained $CaCO_3$, which in places forms thin banks, and an abundance of pelagic diatoms. Zones 1 and 2 alone have benthonic organisms, with the greatest abundance between 210 and 600 feet; the latter is the zone of *Modiola phaseolina* and a great variety of bivalves and gastropods (68 species occur in the shallower waters).

The Kupferschiefer sea, like the Black Sea, had bottom waters with about the average normal salt content, as proved by the typical Zechstein invertebrates. However, because of the lack of oxygen and the high content of sulphuretted hydrogen and CO_2 an abundant bottom life was impossible. That the top water of the Kupferschiefer sea was also fresh is proved by the wide distribution of the freshwater fishes in the sediments, the widely uniform spreading of the thin zone of shale, and the presence of land plants and land vertebrates. If all the water had been salty, the fine muds should have been laid down in a narrow zone bordering the margin of the sea, and this is not the case in the Kupferschiefer sea. The slow decomposition of the organic remains (mainly the plankton) and the lack of oxygen in the depths led further to the formation of the bituminous content (from 6 to 20 per cent.).

As the Black Sea goes down to 7,360 feet, the question must be asked: What was the depth of the Kupferschiefer sea? A positive and exact answer can not be given, but the small thickness of the shale over wide areas, combined with its intimate and variously modified connection below with the Zechstein conglomerate and above with the Zechstein dolomite, and its shallow-water life, show that "it is a deposit of the shallowest and shallower seas." To the reviewer, the depth seems to be well within that assigned the continental shelf seas, *i. e.,* less than 600 feet. The freshwater covering Pompeckj thinks was thin.

Just as in the Black Sea the marginal fresh waters are depositing sands and other littoral sediments that are free of bitumen, so in the Kupferschiefer sea there is some evidence of marginal sands, sandy and clayey limestones, and regions free of metal sulphides.

Later, the black sea of Permian time gradually changed, first locally and finally everywhere, into the limestone-dolomite or Zechstein sea, still, however, an inland sea but devoid of muds and bituminous materials. In the shallow regions nearer the shores arose reefs of bryozoa, but at best the Zechstein sea, even when in widest connection with the ocean, had a small and monotonous fauna.

In an earlier paper Pompeckj[5] discusses a similar deposit, the zone of *Posidonomya bronni* of the Upper Lias of Germany. It seems desirable to cite also some of the details given in this paper, because they are somewhat different from those concerning the Permian. The deposits are fissile, calcareous, bituminous, dark shales rich in iron pyrite. Locally there are also horizons of sandstone, barren of life, and layers of stinking limestone. These deposits are found in northwestern Germany (about 40 feet thick) and France.

In Germany (Swabia and Franconia) the fossils consist of diatoms and coccoliths, horn sponges, very rarely a sea-urchin, crinids (sometimes with stalks over 50 feet long), a few forms of brachiopods, about 18 species of bivalves (of which the only common one is *Posidonomya bronni,* but this very thin-shelled form is at times exceedingly abundant; also *Pseudomonotis substriata, Inoceramus dubius, Pecten contrarius*), and rarely a gastropod or crustacean (Eryon). Besides the common bivalves mentioned, there are many ammonids, belemnids, sepias, fishes (selachians, many ganoids, teleosts), ichthyosaurs, plesiosaurs, and crocodiles. With the marine forms are associated drifted land plants (cycads, and often a great abundance of conifer logs, now carbonized), beetles, and dragons of the air (pterosaurs).

[5] "Die Jura-Ablagerungen zwischen Regensburg u. Regenstauf," Geognos. Jahresheften 1901, XIV. Jahrg., pp. 178–186.

It is apparent from the above that the common fossils are here again those of the nekton (saurians, fishes with most of the ganoids probably of freshwater habitat, belemnids, sepias) and drifted land plants. Of the benthos, only a few species of bivalves are common, and, while the ammonids are also bottom-dwellers and occur commonly as fossils, their empty shells were probably drifted into this black sea. The crinids were also drifted in, for the only specimens found attached are on conifer wood, hanging head downward; otherwise roots of these pentacrinids do not occur.

In general it may be said that the Liassic deposits and the habitat of the fossils of the time of *Posidonomya bronni* agree best with those of the present Black Sea. Since this is true, it follows that the physical conditions of the *bronni* sea must have been very much like those of the Black Sea, *i. e.*, it was a Liassic Black Sea into which drained rivers, causing the surface waters to be more or less freshened, and bringing land plants, logs, and ganoid fishes. However, there are also marked differences, chief among which is the far less amount of decomposition of the soft parts of ichthyosaurians and sepias, of which fleshy parts are often preserved, a condition that never occurs in the Kupferschiefer. Finally, the abundance of the Liassic bivalves points to the shallow waters of the Modiola ooze of the Black Sea, and therefore to depths of less than 600 feet.

It seems to the reviewer that the present Black Sea, with its great depth and widespread foul conditions, is an exceptional example, and that in all of its features it may have no fossil analogue. The Kupferschiefer and *P. bronni* seas along with the American Ohio sea of Upper Devonian time and the Chattanooga sea of the Mississippian period appear to agree with the essential conditions of the Black Sea, except as to depth. All of the fossil Black Seas appear not to have been deeper than 600 feet.

Foul bottoms are clearly due to a lack of water circulation, either because there is no wide connection with the oceanic areas or because there are inadequate vertical or convection currents. The latter conditions may have been more abundantly attained in warm climates than in cool ones, due to the fact that the heavier colder waters sink to the bottoms and so oxygenate them. In this the present is the exceptional condition when compared with most of geologic time. In such stagnant areas, be they small or large in area, or shallow or deep, the oxygen is soon consumed by the organisms of the benthos and the depths become stale and lifeless. As the sulphur bacteria are ever present, but thrive best in the stale bottoms, they soon take the ascendancy there and fill the waters with an ever greater quantity of sulphuretted hydrogen, provided they are furnished with the dead organisms on which to feed and thus to increase in number. On the other hand, the sun-lit, aërated surface waters are the realm of the green and assimilating micro-plants, the free algæ, which convert the inorganic carbon dioxide into their organic bodies, and these upon their death rain into the deeps to form the essential food of the bacteria of the foul bottoms.

That depth of water is not the first essential for the production of foul bottoms has been shown by the examples cited (almost from the surface down), but it does seem that large areas must have depths greater than 300 feet, for otherwise the high waves generated by the storms would set up a vertical circulation and so at least periodically replenish the oxygen and take away the foul gases of these depths. Therefore it would seem that Black Seas of large size should be deep (300 feet or more) and land-locked basins whose oceanic connections are more or less cut off by submerged barriers. Smaller areas are the elongated troughs and rounded holes below the general level of the sea floors, while the smallest and shallowest areas are the bays that are more or less separated from the seas by closely approaching headlands, banks, and bars, or the marine swamps that are filled with eel-grass, mangroves, and other modified land plants.