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Formation and Significance of Black Pebbles from the Ota Limestone (Upper Jurassic, Portugal)

Black Pebbles aus dem Ota-Kalk (Oberjura, Portugal)

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KEYWORDS: MICROFACIES - SEDIMENTOLOGY - SUBAERIAL EXPOSURE - BLACK PEBBLES - CARBONATE PLATFORM - UPPER JURASSIC (OTA LIMESTONE) - PORTUGAL

SUMMARY

Black pebbles are a characteristic facies element of the Upper Jurassic Ota carbonate bank (Portugal). They occur both scattered or concentrated in two horizons, the upper of which is very widespread and may serve as a lithostratigraphic correlation level.

Blackening is mainly due to plant material. Organic matter infiltrated soft or slightly cemented sediments as well as solution cavity fillings within cemented limestones.

Black pebbles are in part transported and found in narrow alluvial fans, beach conglomerates and lagoonal settings. Others represent parautochtonous relics of hard brecciated black crusts which were reworked during a local transgression.

Subaerial exposure, leading to the blackening and subsequent distribution of black pebbles, is due to local block-fault tectonics. These are related to the Vila France fault system, which formed during a pronounced rifting phase in the Lusitanian Basin.

ZUSAMMENFASSUNG

"Black Pebbles" stellen ein charakteristisches Element der oberjurassischen Ota-Karbonatbank (Portugal) dar. Sie treten einzeln auf, konzentrieren sich jedoch insbesondere auf zwei Horizonte, von denen der höhere weit verbreitet auftritt und als lithostratigraphischer Leithorizont dienen kann.

Die Schwarzfärbung wird durch Pflanzenmaterial verursacht. Das organogene Material infiltrierte unverfestigte oder nur leicht zementierte Sedimente, aber auch Verfüllungen von Lösungshohlräumen innerhalb bereits verfestigter Kalke.

Die "Black Pebbles" wurden teilweise tranportiert und finden sich dann in kleinen Alluvionenfächern, Küstenkonglomeraten und lagunären Milieus. Zum Teil stellen sie jedoch parautochtone Relikte harter, brekziierter, schwarzer Krusten dar, welche während einer lokalen Transgression ausgespült wurden.

Das Trockenfallen, welches zur Schwärzung der Sedimente führte, sowie die anschließende Verteilung der schwarzen Gerölle hat seine Ursachen in bruchtektonischen Ereignissen entlang der Vila Franca Störungszone. Diese Ereignisse stehen im Zusammenhang mit einer intensiven "rifting"-Phase des Lusitanischen Beckens.

INTRODUCTION

The Ota Limestone is a tectonically delimited limestone horst situated in the Lusitanian Basin (Fig. 1). The ca. 150 m thick limestones most likely represent an intrabasin carbonate bank, eventually on an uplifted basement block (cf. LEINFELDER 1986; in press).

The very pure limestones comprise a wide range of facies types, namely reefoid, bioclastic , intraclastic and oncolitic high energy facies, loferitic sequences, and low-energy bioclastic, oncolitic or intraclastic facies. Facies types are roughly arranged into zones (Fig. 3; LEINFELDER et al. in prep.).

Internal lithostratigraphic correlation is made difficult due to partly rapid lateral facies changes and tectonic complications. However, useful and easily recognizable marker beds are horizons exhibiting black pebbles. Black pebbles, i.e. blackened lithoclasts or fossil fragments

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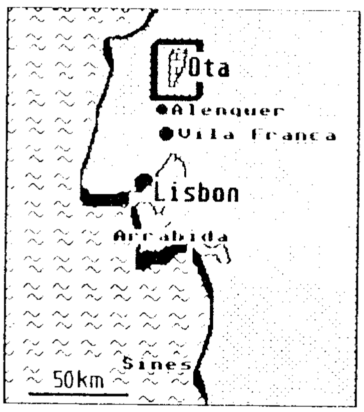

Fig. 1. Location of working area (small frame) and sites mentioned in the text.

appear widespread throughout the Ota Limestone. In the north of the Ota they occur scattered within low-energy limestones. On the other hand, black pebbles are abundant in two horizons, the upper of which can be traced over almost the entire Ota area (Fig. 2).

This short communication gives an overview of the pebbles and their host sediment, and considers the conditions of blackening and the mechamisms of reworking and pebble distribution.

THE BLACK PEBBLES

Black pebbles of the Ota Limestone measure between 0.3 and 120 mm, mean size is only 2 mm (Fig. 4).

Sorting of black pebbles within one sample may occasionally be good, commonly, though, very poor (extremes from 0.5 to 100 mm). Black-pebble quantities range from << 1 % to 60 %. The average of all samples for the upper black-pebble level is 8 %. Black pebbles are commonly subrounded to rounded, angular or lobed types occur as well. Common are flattened or even triangular outlines (Pl. 18/1, 2).

Normally black pebbles consist of black lithoclasts; isolated blackened bioclasts may rarely appear, most common are blackened corals and nerineids. Often, such bioclasts seem to be lithoskels reworked from lithoclasts and give evidence of intermittent reworking. Also isolated oncoids may be blackened (Pl. 18/3).

Primary facies of black lithoclasts is identical with facies types known from the unaltered Ota Limestone. Hence, mudstones, bioclastic, oncolitic or intraclastic wackestones, fenestral wacke-/packstones (rarely), and intraclastic-peloidal pack-/grainstones appear. Somehow contrasting with the unaltered Ota Limestone is the good sorting of commonly occurring blackened peloidal and oolitic grainstone facies, the latter type of which is not very frequent in the Ota Limestone (LEINFELDER et al. in prep.).

Often the original facies is difficult to decipher, due to the strong vadose diagenetic overprint from which nearly all pebbles suffered. Meniscus and dripstone cements are locally well developed (Pl. 18/5) and much more frequent in black pebbles than in the rest of the Ota limestone. Original micrite is often altered to microspar and neospar (Pl. 18/6), so that components within the pebbles often become indistinguishable. Neosparitization may also affect sparitic types. Additionally, black pebbles frequently display up to mm-sized, regular and irregualar solution vugs which may be partly filled by internal sediment or vadose silt. Occasionally, black pebbles are completely calichefied. They may also exhibit calcitic cracks and veins ending at the pebble margin, which indicates that they formed prior to the deposition of the pebbles.

Degree of blackening may vary between pebbles within one sample (Pl. 18/2) but also within one single pebble (Pl. 18/1). Colors range from brownish to medium-gray to bluish black. Within one sample both the smaller and the micritic pebbles tend to be darker than larger and/or sparitic types. Black pebbles may contain unblackened components, e.g. small oncoids and particularly echinoid fragments, or smaller pebbles which are darker than the host pebble. Sometimes black pebbles exhibit a lighter or darker rim, or consist of an aggregate of gray clasts which are agglutinated to each other by black, algal-like crusts.

THE HOST SEDIMENTS

Frequently, isolated black pebbles occur in low quantities in component-poor mudstones and fine bioclastic wackestones. Although mostly of small size (1-3 mm), they represent the largest particles. A 12 cm-large black pebble was found in a fine biointrapel-wacke-/packstone with an average grain size of 0.5 mm (Pl. 18/4).

Poorly sorted bioclastic-intraclastic packstones may contain up to 40 % of relatively large black pebbles. Again the black particles represent the largest components. Black pebbles rarely occur in micritic or intraclastic limestones with laminated fenestral fabric (loferites).

Black pebbles appear most commonly and most typically in oncolitic limestones (Pl. 18/2), particularly in oncointrapel-packstones with a weak bipolar grain size distribution. The large oncoids typically exhibit a black-pebble nucleus. At times the micritic matrix as well as the intraclasts and the peloids are also blackened (medium gray), so that oncoids, save their black nuclei, are the only light-colored constituents of the rock. Except for very large specimens, black pebbles are all coated by oncoidal layers.

The most spectacular black-pebble host rocks are lithoclastic conglomerates (packstones) (Pl. 18/1), locally with up to 25 cm large clasts. Black pebbles are commonly smaller than unblackened lithoclasts and exhibit very variable degrees of blackening. At some sites, conglomerates are almost entirely composed of black pebbles (up to 60 % of the whole rock). Fine-grained lithoclastic packstones, partly with a low admixture of bioclasts, are also commom (Pl. 18/3).

Sorting of components is very poor but at times shows weak bipolarity. Most particles are subrounded to subangular. The lower limit of component size is difficult to determine, i.e., components grade continuously in a silt-sized matrix. Spar-filled shelter pores are frequent in some samples.

Packing is generally dense. Long-grain contacts, local imbrications and subvertical positions of elongated particles are very frequent; large clasts, however, commonly float in a densely packed, fine-grained conglomerate. Some of these are very poorly cemented. Exceptionally, friable conglomerates exhibit an insoluble fraction of silt-sized quartz and clay minerals up to 9 %.

In black-pebble bearing facies-types, detrital quartz appears locally in low quantities, mostly as isolated, in one case up to 2 cm large grains (Pl. 18/7).

THE MAIN BLACK-PEBBLE HORIZONS: VERTICAL AND LATERAL DEVELOPMENT

Besides common subordinate black-pebble horizons which can be correlated only locally or not at all, two levels can be traced over long distances.

The lower level is cropping out perfectly well at the former Relva quarry (Figs. 3, 5) and can be found again at the eastern exit of the Ota river valley and within the valley itself. At Relva the 4-5 m thick level consists almost completely of thick-bedded coarse black-pebble conglomerates which show vague grading, primary gentle dip, inconstant bedding thicknesses and wedging-out of horizons towards the south. Black pebbles show the entire range of the above described characteristics in facies composition, diagenetic overprints and differential blackening. In the middle part a poorly cemented layer is intercalated. A reddish wackestone with fine bio- and lithoclasts and larger floating black pebbles appears locally. Upper and lower bedding planes are commonly irregular. The black-pebble horizon is topped by oncolitic wackestones exhibiting small oncoids and mm-sized black pebbles. Black pebbles then disappear in the superimposed fine bioclastic mud/wackestones which occasionally contain coral fragments (Fig. 5).

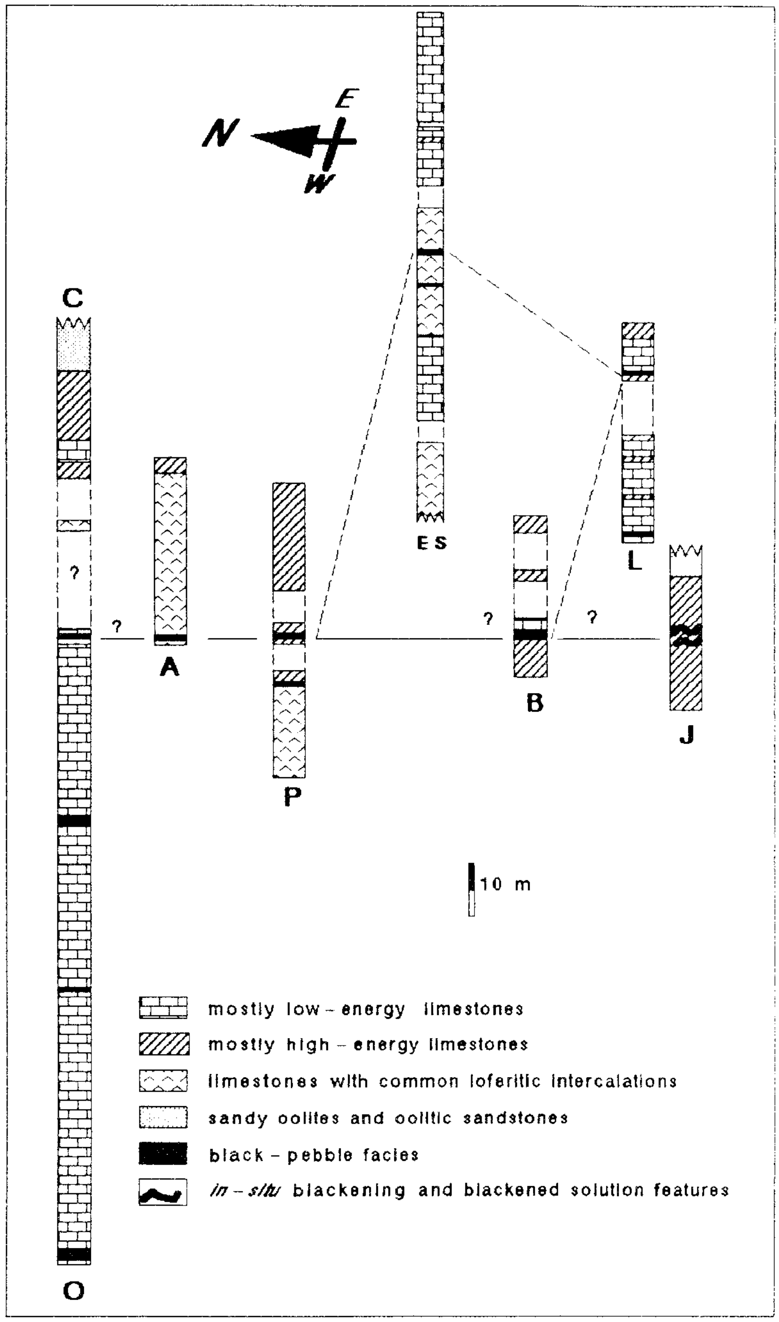

Fig. 2. Simplified main sections of the Ota Limestone. Correlated by the upper main black-pebble horizon. For locations see Fig. 3.

1 km further south at the eastern exit of the Ota valley the level reappears as a 0.5 m thick, partly sparitic, black-pebble conglomerate with maximum grain sizes of only 3 cm. It is overlain by mud/wackestones and packstones containing only scattered black pebbles in quantities diminishing upwards. The horizon appears once more 900 m further northwest in the same valley (section 0, Figs. 2,3), where it consists of 1.5 m of wackestones containing low quantities of black pebbles.

The upper, main black-pebble horizon can be traced over almost the entire Ota (Fig. 2). It exhibits a very strong variety in facies, black-pebble content and black-pebble sizes over short distances (Figs. 6,7). Except for the south of the Ota, the horizon always contains oncolitic intraclastic pelletal packstones exhibiting black pebbles in the oncoid nuclei (Pl. 18/2). Black pebbles contents range from few percent up to 55 % (Fig. 7). In the central-eastern area this oncolitic level is biobored and

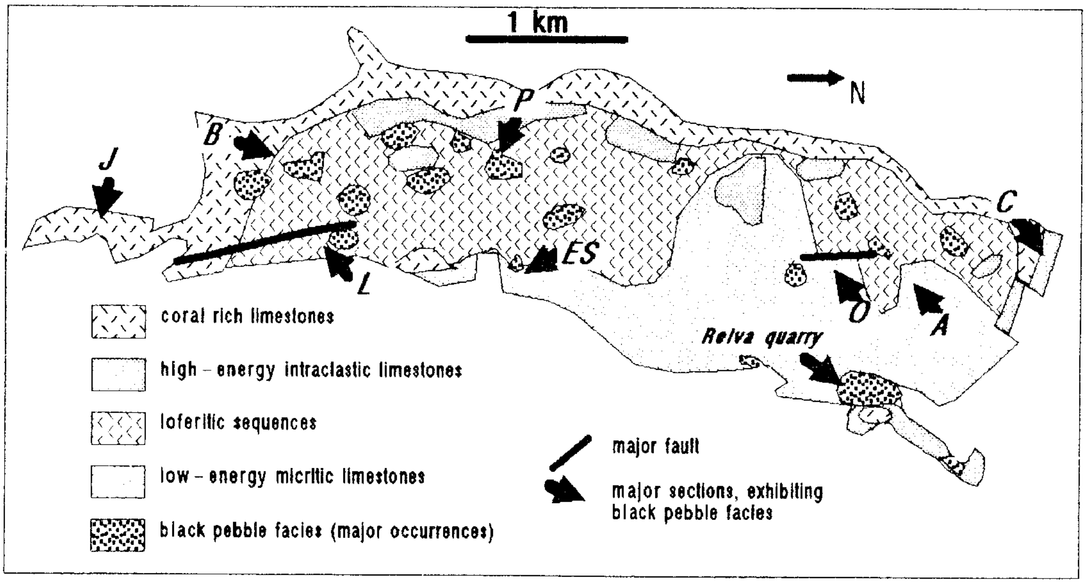

Fig. 3. Simplified facies map of the Ota Limestone, distribution of important black-pebble outcrops and setting of the mentioned sections.

underscored, thus clearly displaying hardground features. Lithoclastic packstones are associated at almost all sites, but are much finer-grained than those of the lower black-pebble horizon. They are commonly poorly cemented and may exhibit admixtures of bioclasts and blackened oncoids (Pl. 18/3). Loferites, bioclastic-intraclastic pack/grainstones and mud/wackestones with isolated small black pebbles may also occur.

Black-pebble sizes are largest at the Bairro section in the south (5-40 mm; max. 120 mm), where black pebbles mostly display component-rich facies, often with coral fragments. Towards the north micritic pebbles dominate, and maximum grain sizes decrease (Fig. 7). Grain sizes and frequencies are, however, very variable and may considerably differ already over a distance of only a few meters.

Blackening of the matrix is occasionally, blackening of solutional features very commonly associated with this main black-pebble horizon (Fig. 6). In the south of the Ota (Section J, Fig. 2) the horizon displays blackening only of primary sediments, fissure fills or internal sediments in solution vugs (Pl. 18/8). 1.5 km south of the Ota region, in an isolated outcrop at Alenquer, these features are again associated with isolated black pebbles and most probably belong to the same level.

THE ORIGIN OF BLACKENING

Black pebbles are known from various Phaneroic rocks, although reports are rare. (For a review of the literature see STRASSER & DAVAUD 1983). Recent and sub-recent occurrences were reported, e.g. by WARD et al. (1970) and BARTHEL (1974). STRASSER & DAVAUD (1983) gave an excellent synopsis of what is known about black-pebble formation and added many new data from the Purbeckian limestones of the Swiss and French Jura. They concluded that the blackening agent is chiefly organic plant material, infiltrating mainly unconsolidated carbonate sediments in high PH / low EH intertidal, supratidal and terrestrial settings such as ponds, lakes or soils (see also FRANCIS 1986). Infiltration of organic matter induces rapid neomorphism, cementation and thus fixation of the black color. Such altered

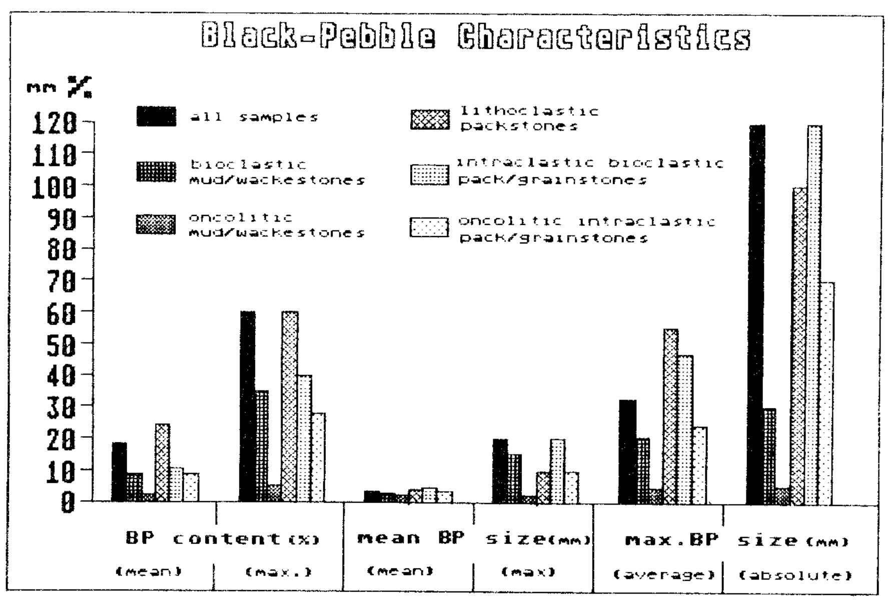

Fig. 4. Size and frequency distribution of black pebbles of the two main black.pebble horizons (based on 105 samples and field observations).

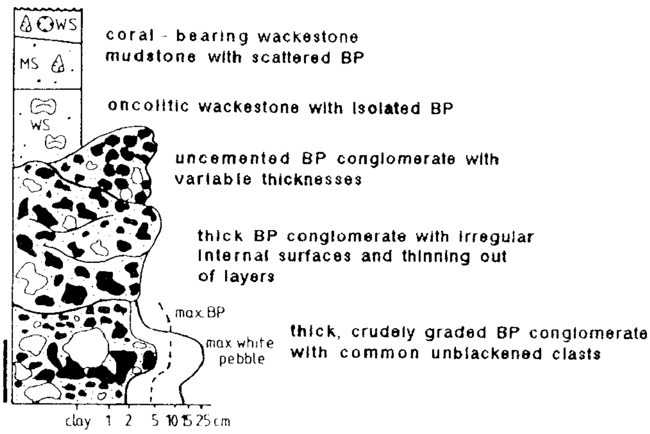

Fig. 5. Simplified section of the Relva quarry. For location see Fig. 3.

sediments have a higher preservation potential than associated, unblackened, soft sediments. STRASSER & DAVAUD (1983) thus follow earlier workers (e.g. HÄFELI 1966, WARD et al. 1970, BARTHEL 1974, FLÜGEL 1978), in that black-pebble occurrences are diagnostic indicators for partial to complete subaerial exposure of subsequently reworked carbonate deposits.

Coloration of Ota black pebbles is clearly derived from organic matter. Content of organic carbon is up to 0.4 %. Lower values (0.15 %) result in medium to dark gray coloration.

Differential thermal analysis (using Al_2O_3 as innert substance; carbonate dissolved with formic acid) reveals a broadly shaped carbon oxidation curve, exhibiting two weak to strong peaks (around 330-340° C) and a steeply inclined high temperature flank (Fig. 8), thus clearly indicating organic matter (SMYKATZ-KLOSS 1974). According to STRASSER & DAVAUD (1983) the low temperature peak indicates kerogene eventually derived from algal material, whereas the second peak and the following steep flank corresponds to coalified matter which originated from higher terrestrial, possibly burnt, land plants. However, the peaks might only correspond to secondary products of further differentiated primary organic matter.

Blackening in the Ota occurs besides in discrete black pebbles also within the primary matrix and, very commonly, in solution cavity and fissure fills (Pl. 18/8, 10). Black internal sediment, filling leached coral cavities, yields a CO_2-curve similar to those of isolated black pebbles, whereas the black filling of a subhorizontal solution cavity within an mud//wackestone produces a differently shaped curve whose shape is similar to that of elementary sulfur or certain iron sulfides (SMYKATZ-KLOSS 1974). Iron content is exceptionally high (0.73 %, expressed as FeS_2). Comparable small peaks also occur in some black pebble curves.

Blackening of solution cavity fillings can affect irregular areas larger than 100 cm^2. Blackened cavity fillings are often finely laminated. Reworked black pebbles occasionally exhibit this fabric. More commonly neosparitization destroys the original structure. Very rarely, small black pebbles were found in unblackened karstic fillings.

Locally, angular large black pebbles lying within low energy micrites and associated with subaerial solution features are clearly pseudopebbles which originated in-situ due to local solution and subsequent blackening of internal fillings along small fissures (Pl. 18/10).

Black pebbles have been found associated with reworked speleothemes (ESTEBAN & KLAPPA 1983) or directly within karstic cavities (BECHSTÄDT 1975, BECHSTÄDT & DÖHLER-HIRNER 1983, HENRICH 1984).

STRASSER & DAVAUD (1983) mentioned that in the Purbeckian limestones of the Swiss and French Jura blackening of solution cavity fillings does not occur due to large crystal size and hence poor adsorption of the

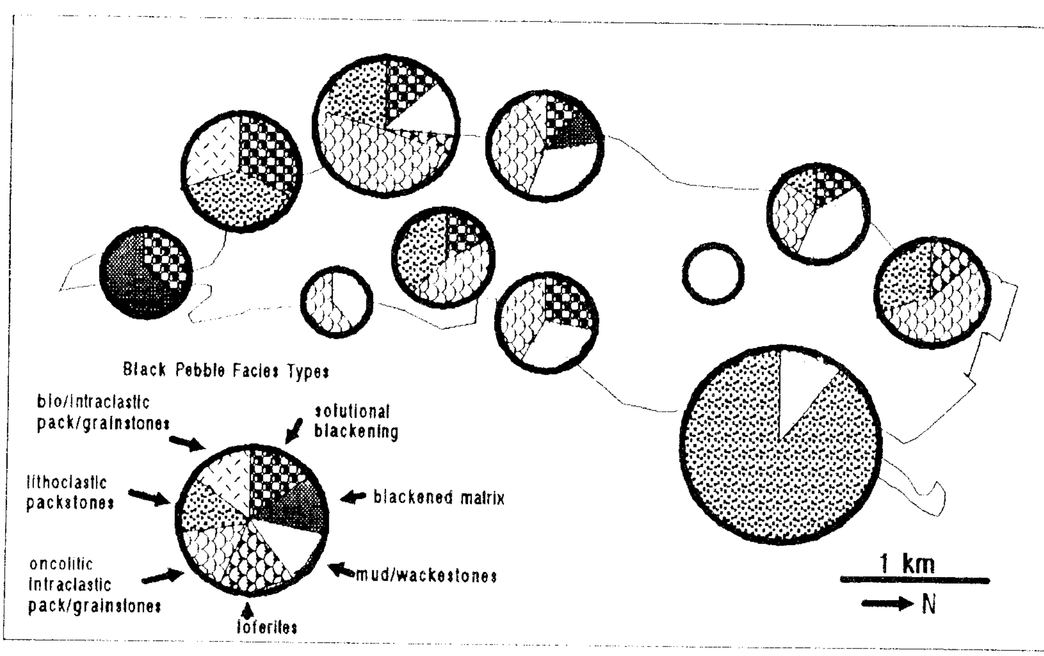

Fig. 6. Relative distribution of black pebble bearing facies types and blackening phenomena in the main black-pebble horizons (based on 105 samples and field observations).

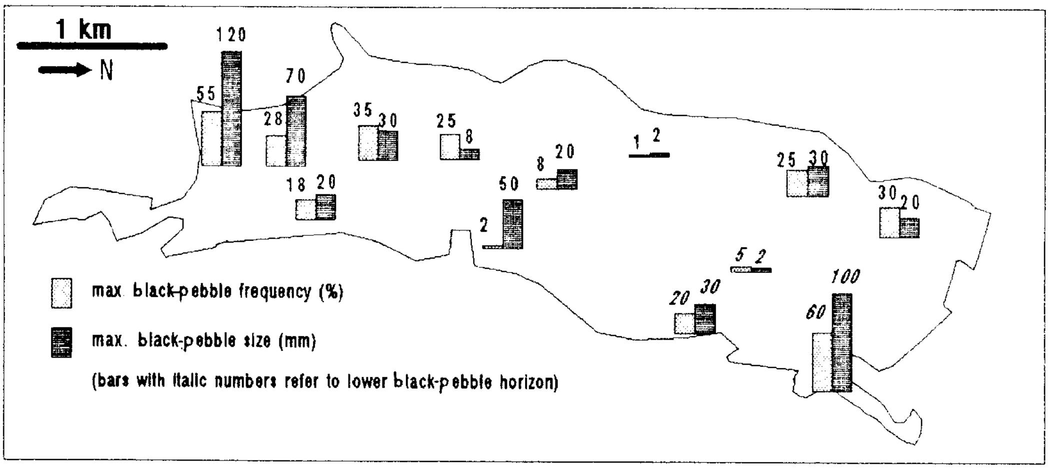

Fig. 7. Lateral distribution of maximum black-pebble frequency and size for the upper and lower black-pebble horizons

organic matter. In the Ota limestone , however, cavity fillings are fine-grained and production of the organic matter, e.g. in vegetated karstic sinkhole ponds was probably high. Oxygen-depleted fluids rich in organic colloids and sulfur derived from plants could migrate downwards to infiltrate and harden residual sediments.

BLACK PEBBLE DISTRIBUTION

Black pebbles are sometimes found in tempestites (e.g. BLÄSLI 1980 in STRASSER & DAVAUD 1983, AIGNER 1982; see also Fig. 5 of GYGI & PERSOZ 1986). Black pebbles may also be associated to their original environment such as soils (FRANCIS 1986, BECHSTÄDT & DÖHLER-HIRNER 1983), beach rocks (INDEN & MOORE 1983) or tidal and lacustrine ponds (FELBER et al. 1982, LEINFELDER 1983). STRASSER & DALVAUD (1983) identified them also from beach conglomerates and tidal channels.

The lower black-pebble horizon of the Ota Limestone exhibiting the thick coarse black-pebble conglomerates, clearly has a fan-like distribution. The Relva quarry section exhibits all criteria of a narrow subaerial fan deposit: irregular bedding planes, through fillings, wedging out of layers, primary low-angle dip, large grain size, chaotic position and occasional imbrication of pebbles, crude grading, lack of distinct internal structures, weakly bimodal sorting, partly washed sieve deposits with shelter pores, and matrix-supported debris flow layers. (BULL 1972, COLLINSON 1986). Rapid jumps in grain size distribution indicate a tectonically active source area. The predominance of black pebbles implies that mainly blackened hard crusts were eroded. Subordinate, yet of larger size are white clasts. Their very poor rounding rather points to shorter transport than to primary smaller blackened clasts which could have been created by in-situ rhizo-breccation or weathering of the black crusts as it is the case for some Purbeckian black-pebble occurrences in England (FRANCIS 1986).

Intercalations and superposition of marine horizons are evidence for the proximity of the coast. Better sorted and rounded pebbles might be due to coastal reworking.

Black pebbles containing the dasyclad *Heteroporella lusitanica* (Pl. 18/6) are most likely derived from the north-east, where there is a closeby limestone exposure (Mt. Redondo) exhibiting a level with this alga, it was not found in the Ota region s.str. (LEINFELDER et al. in prep.).

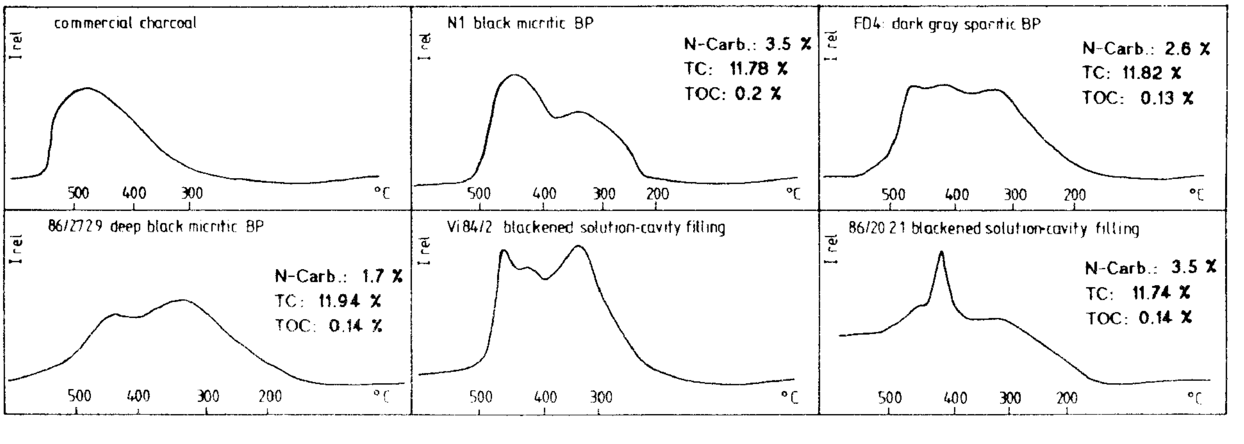

Fig. 8. Carbon oxidation curves from differential thermal analyses for selected black pebbles and blackened sediments, and content of total carbon(TC), organic carbon (TOC) and non-carbonate fraction (N-Carb) in weight percent.

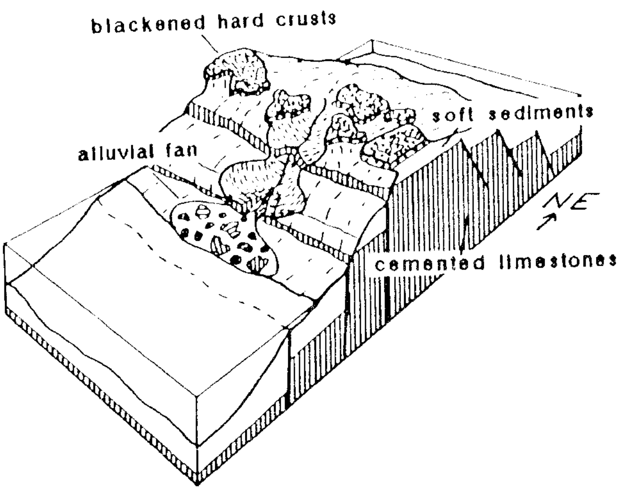

Fig. 9. Depositional model for black-pebble distribution in the lower black-pebble horizon. For further explanation see text.

Apparently the region was tectonically slightly lifted, so that sediments were positioned in the supratidal or a slightly higher level. This happened along faults of the Vila Franca Fault System which was active already during the Upper Jurassic (WILSON 1979, LEINFELDER 1986, in press). On such subaerial mud banks and sand cays widespread blackening and related hardening of sediments took place. Isolated cm-sized detrital quartz grains were occasionally carried to the local beaches through stranding drift wood.

Millimeter to centimeter-sized detrital quartz occurs scattered in isolated grains throughout the entire Ota Limestone (Pl. 18/7). Quartz is most likely derived from the eastern hinterland. Purity of the Ota intrabasin bank limestones (normally 98–99% $CaCO_3$) excludes, however, admixture due to storms, since quartz grains are not enriched in horizons and are not associated with a terrigenous clay fraction. The nature of the hinterland as well as the sediments underlying the Ota Limestone are not known; a small carbonate bank further south, however, similar to the Ota Limestone (Monte Gordo Limestone, closeby Vila Franca) is underlain by km-thick coarse alluvial/submarine fan sediments, consisting of arcosic quartz conglomerates (LEINFELDER in press). Possibly, such sediments also underlie the Ota Limestone, situated in the same geotectonic position as the Monte Gordo Limestone, and eventually also formed the hinterland at the time of deposition of the Ota Limestone. Trees on the coast were possibly uprooted during storms and trunks with quartz pebbles caught in the roots floated seawards. Pebbles dropped occasionally into the submarine Ota sediments or, more frequently, stranded at the coasts of islands where blackening processes took place.

Further accentuated uplift caused strong relief and thus gravitational energy potential. This resulted in rapid erosion of the hard, blackened limestones and incorporated the rafted quartz grains. Erosion cut through the underlying unconsolidated sediments to finally erode deeper, already diagenetically cemented, unaltered parts of the Ota Limestone. The reworked limestones were deposited at the morphological break in front of the uplifted block (Fig. 9).

The history of black-pebble distribution in the upper black-pebble horizon is more complex. A depositional model can be outlined as follows (Fig. 10):

Apparently due to tectonic uplift, major parts of the Ota complex underwent partial (inter/supratidal) or complete subaerial exposure. In the western part of the Ota, uplift was strongest or longest, since partly or completely cemented high energy rocks underwent partial karstification, particularly along fissures and faults. Caliche crusts occasionally covered the karstified morphology (Pl. 18/3), and exposed uncemented carbonate sands were reworked by wind to form eolian dunes.

Blackening of sediments due to organic matter occurred in vegetated karst sinkholes, along fissures, open faults and solution pipes, and in vegetated interdune areas, thus giving blackened and cemented eolianites a higher preservation potential than the normally eroded primary dunes. Uplifted algal mats were rarely blackened because they already consolidated soon after their deposition. Instead they partly developed perfect vadose cements. Exposed subtidal calcareous muds further east were, frequently blackened in intertidal and supratidal and inland ponds. Again, isolated quartz pebbles dropped in the coastal areas through transport by driftwood. This wide area was subsequently flooded except for a narrow island chain.

Facies spectrum in black pebbles commonly corresponds roughly to the facies pattern of the sediments they are embedded in, i.e., coral- and bioclast-rich black-pebble facies occurs within the zone of coral and bioclastic limestones; micritic pebbles are commonly found in micritic sediments. This indicates that pebbles were not transported very far.

Unconsolidated fine sediment was winnowed, so that blackened brittle zones remained as parautochtonous, up to 12 cm large relics in relatively low energetic sediments (Pl. 18/4, 9). In shallower settings, blackened crust relics were slightly reworked and encrusted by cyanophyte algae. Such oncoid formation was widespread due to relatively low sedimentation rates in the course of this local transgression. Along the coast, reworked black pebbles and caliche clasts, lithoskels and bioclasts formed coastal conglomerates which were partly storm or spring-tide induced. Several blackened zones, particularly subsurface solution-cavity fillings were not reworked but preserved in-situ.

CONCLUSIONS AND DISCUSSION

1) First examinations indicate that the Upper Jurassic Ota Limestone from Portugal most likely represents an isolated, Bahama-like, roughly zoned, narrow carbonate

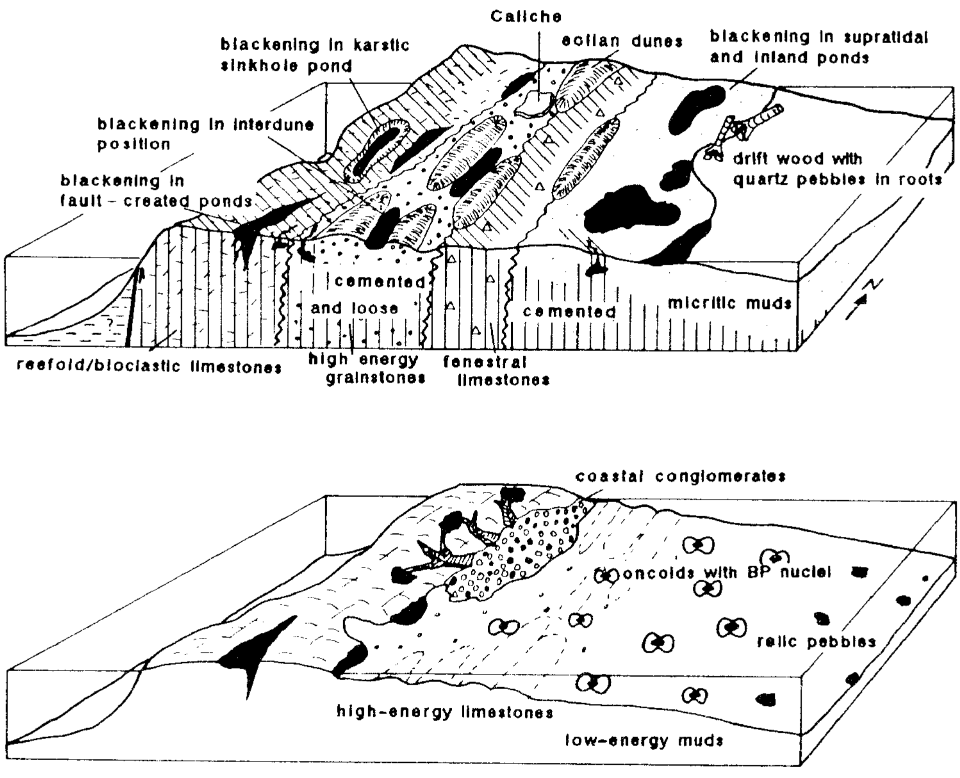

Fig. 10. Models for blackening (upper picture) and black-pebble sedimentation (lower picture) in the upper black-pebble horizon. See also text.

bank. Black pebbles occur scattered and in very low quantities except for two levels where black pebbles amount up to 60%. The upper level can be traced across almost the entire Ota complex.

2) DTA-analysis reveals that the blackening agent is most likely derived from land plants and algae; related processes like preferential cementation, differential dissolution and neomorphism are identical with the processes outlined by STRASSER & DAVAUD (1983) for Purbeckian pebbles from Switzerland and France. Blackening also occurs within karstic solution cavities, fissures and dykes, if cavity fillings are sufficiently fine-grained.

3) Black pebbles can easily be confused with patchy in-situ blackening of solution-cavity fillings, particularly when in semifriable sediments the blackened and thus harder patches become accentuated by differential compaction.

4) Isolated, small or up to 12 cm large, subangular black pebbles or black-pebble clusters occurring in low-energy facies are not necessarily transported but rather represent winnowed, parautochtonous relics of weathered or rhizo--brecciated black crust. A certain vertical redistribution by burrowing organisms or gravitational sinking into the lower soft sediments must, however, be taken into account.

5) High black-pebble percentages appear particularly in oncolitic limestones and lithoclastic packstones (conglomerates). Storm-transported or relic in-situ black pebbles were preferably encrusted by cyanophyte algae during a transgressive period characterized by low sedimentation rates. Lithoclastic packstones represent different environments such as storm deposits, coastal conglomerates and small alluvial fans.

6) Isolated, rare detrital quartz (up to cm-size) derived from the siliciclastic hinterland and released from driftwood stranded at the local islands. Clay-sized insoluble residue of unaltered Ota Limestone is very low (1-2%), but amounts up to 3.5% in some black pebbles and up to 9% in several poorly cemented black-pebble conglomerates. This can be explained by eolian transport from the hinterland or by concentrating clay fraction due to partial solution of limestones. Further examinations are needed.

7) Blackening and related hardening mainly affected uncemented sediments, since vadose cements are far more common in black pebbles than in unblackened deposits. As a consequence, sediments with an otherwise low preservation potential, e.g. eolianites, may be preserved as black pebbles, permitting to conclude the former environment.

8) Black pebbles are taken as indicative for eustatic sea level fluctuations (BARTHEL 1974, FLÜGEL 1978). Occurrences of isolated black pebbles throughout the Ota Limestone demonstrate, however, the existence of small

low–relief islands during most of the depositional time. The lower black–pebble horizon has a limited fan–like distribution. Pebbles derived from the northeast. This evidences local block faulting along the Vila Franca Fault System in the course of the second rifting phase of the Lusitanian Basin. Deposition of the narrow alluvial fan was rapid, so that the horizon represents a local, roughly isochronous marker bed.
The upper horizon was due to a general uplift of the Ota and subsequent return of the sea. Uplift was strongest in the southeast and northeast. It is not clear whether these movements were completely coeval. Reworking of blackened facies mainly by coastal erosion was not necessarily synchronous. Hence, this level represents an useful field correlation horizon, but is not a synchronous marker bed.

8) Upper Jurassic black pebbles of the Lusitanian Basin occur at different times and in different environmental settings: In the Serra da Arrabida they are associated with brackish to freshwater marls, overlying a Lower Oxfordian unconformity (RAMALHO 1971, FELBER et al. 1982, LEINFELDER 1983). They also occur in associated limestone conglomerates exhibiting red groundmass and white and rubefied pebbles, as well as within and on top of Kimmeridgian marine limestones, where they are partly associated with blackened caliche (LEINFELDER 1983). At the southern beach of Cabo de Sines, they appear in a karstic fissure filled with multicolored conglomerate similar to the Arrabida one. Isolated black pebbles could be also found in the shallow–water facies of the Upper Oxfordian Montejunto Limestone. The Ota Limestone is partly surrounded by Upper Kimmeridgian/Lower Tithonian freshwater oncolites (LEINFELDER 1985) which contain very rare, small black pebbles. They formed in associated subenvironments or are eventually also derived from the exposed Ota Limestone. At Monte Gordo, black pebbles appear at a tectonically created slope break at the transition between very thick siliciclastic arcosic fans and carbonate sediments.

Following STRASSER & DAVAUD (1983) and earlier workers, black–pebble occurrences are valuable tools for identifying partial or complete subaerial exposure of limestone. Layers rich in black pebbles do, however, not necessarily correspond to eustatic sea level fluctuations. Taking lateral distribution characteristics into account, they may as well be an important tool to unravel paleotectonic small–scale movements.

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Plate 18 — Black pebbles and blackening phenomena from the Ota Limestone (Upper Jurassic), Portugal

Black Pebbles aus dem Otakalk (Oberjura) von Portugal

Fig. 1. Black–pebble conglomerate. Note occasional imbrication fabric and differential blackening within individual pebbles and graded bedding. Top of sample to the left. Alluvial fan deposit. Relva quarry, polished slab, RV 10, x 0.9

Fig. 2. Oncolitic peloidal packstone. Note varying intensity of blackening. Black pebbles mostly display high–energy facies. Large gray clast (upper right) is not coated by algae. Lagoonal facies, possibly storm–reworked. Southwestern Ota, polished slab FD 11, x 0.8

Fig. 3. Weathered and leached oncolitic intraclastic packstone, exhibiting karstic relief; overlain by thin caliche crust and black–pebble packstone containing blackened oncoids. Black–pebble packstone also contains bioclasts (not visible at this scale).
Coastal conglomerate, possibly storm–induced. Southwestern Ota, polished slab 85/8.3.2, x 0.8 (arrow).

Fig. 4. Large irregularly shaped black pebble embedded in pelmicritic low–energy facies. Note leached vugs and borings (white spots) in pebble. Black pebble is interpreted as in-situ fragment of black crust, fine sediment was winnowed out, black pebble stayed behind as lag deposit. Bairro Section polished slab, 86/26.2.21, x 0.6

Fig. 5. Facies of isolated black pebble displaying blackened grainstone facies. Note thick vadose cements. Dripstone cements are not any more geopetally directed, i.e. vadose cementation was prior to transport. Black pebble from sample shown in Fig. 2. Thin section FD 11, x 8.8

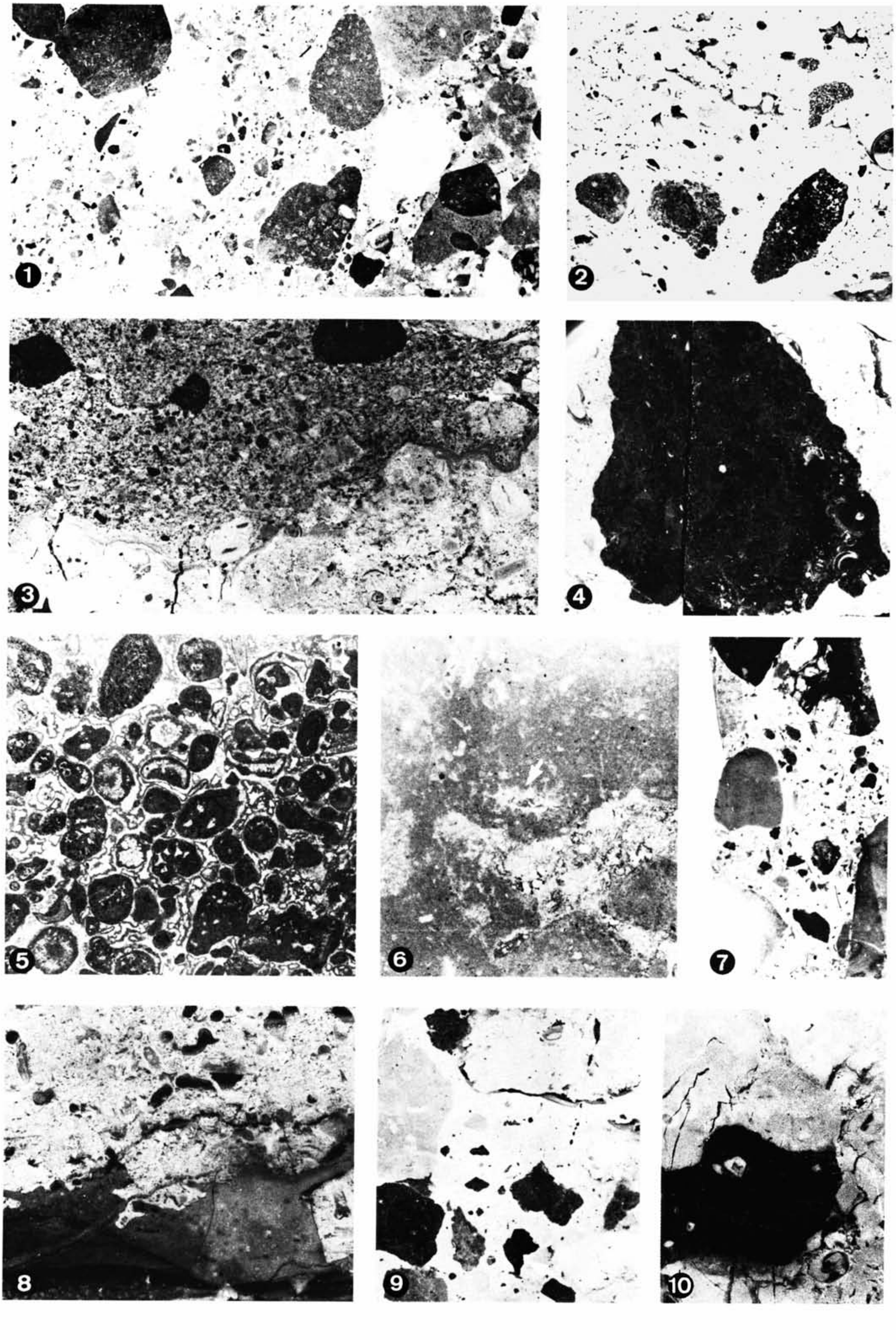
Fig. 6. Micritic black pebble. Note solution vugs, microspar patches and remains of the dasyclad *Heteroporella lusitanica* (arrow). Relva quarry, peel 85/2.10.23, x 15.6

Fig. 7. Black–pebble conglomerate with partly open fabric and large detrital quartz pebble (lower left). Note calichefied pebble (arrow). Debris flow within alluvial fan. Relva quarry, polished slab 85/2.10.24, x 1.2

Fig. 8. Coral–peloidal grainstone exhibiting large solution cavity filled with blackened sediment. Corals mostly leached, biomolds partly with black infill. Southernmost Ota, Alenquer quarry, polished slab 85/23.9.8, x 1.5

Fig. 9. Black–pebble wackestone with very angular black pebbles. Note solution vug, partly filled with gray internal sediment. Left arrow: shelter pore. Black pebbles represent relics of black crust. Northwestern Ota, polished slab 86/26.2.9, x 0.7

Fig. 10. Black pseudopebble, due to completely filled and blackened solution cavity. (Cavity is reduced to irregular black cracks at the back of the sample, not visible). Northernmost Ota, polished slab 86/24.2.5, x 1.5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