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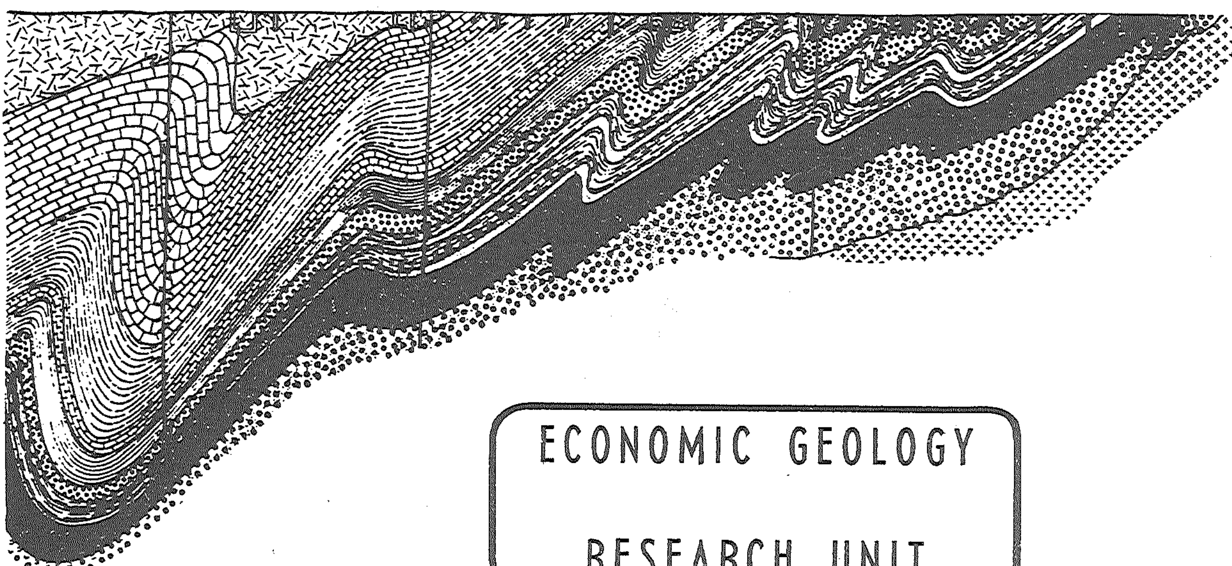

ECONOMIC GEOLOGY

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STRUCTURES IN PYRITE FROM THE BASAL REEF IN THE ORANGE FREE STATE GOLDFIELD

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by

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ABSTRACT

Pyrite constitutes generally over 90 per cent of the ore-minerals in the Basal Reef of the Witwatersrand System. It occurs as rounded detrital grains, as pseudomorphs, as concretions and as secondary idioblasts, encrustations and veinlets. Rarely, pyrite was found to be hydrothermally emplaced. The variety of pyrite forms necessitated a descriptive classification. The relative abundance of different micro-spherical structures of the "mineralized bacteria" type is a striking feature of the portion of the Basal Reef studied. The possibility of an anaerobic environment in the Witwatersrand basin, during a period of quiescence just after the deposition of the conglomerates, is discussed, and found to be feasible. Anaerobic conditions, however, existed only in small areas and it is pointed out that the Basal Reef in parts of the Free State Geduld area might represent such an anaerobic pocket. It is believed that in these anaerobic environments sulfate-reducing and H_2S generating microbes existed. The biogenically formed H_2S was responsible for the formation of pyrite pseudomorphs and pyrite concretions. It is furthermore pointed out that the existence of precipitated ferrous sulfide would also provide an explanation for the distinctly selective mobilization of the Witwatersrand pyrite: the compact detrital pyrite was to a large extent resistant to mobilization, whereas the precipitated, amorphous ferrous sulfide was mobilized and reconstituted. The postulated existence of life in the Witwatersrand basin agrees with recent studies of the structure, biochemistry and carbon isotope distribution of the Witwatersrand thucholite, all of which indicate the existence of primitive life in parts of the depositional basin of the Witwatersrand conglomerates.

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INTRODUCTION

Of the ore-minerals in the Witwatersrand conglomerates by far the most abundant is pyrite. In many cases the pyrite, which constitutes over 90 per cent of the ore-minerals, appears to be the only macroscopically identifiable ore-mineral. Generally it occurs disseminated throughout the entire width of the ore-horizons, but in many instances it is concentrated in false footwalls and in footwall contacts. The notably rounded shape of many pyrite grains in the Witwatersrand conglomerates (approximately 50 to 75 per cent of the total pyrite content) has aroused the interest of many students of the ore-body, since pyrite normally exhibits idiomorphic outlines. Becker (1896) described these rounded pyrite grains as "pyrite pebbles" and accordingly interpreted them as being detrital components of the conglomerates. Later, however, Young (1917), Horwood (1917), and Graton (1930), to name only a few, considered that the rounded pyrite grains represent replacements of rounded quartzitic and other components of the conglomerates. Consequently, these authors postulated a hydrothermal-epigenetic origin for the pyrite in the Witwatersrand ores. Many of the more recent observations made on the Witwatersrand pyrite oppose an epigenetic origin and it is now believed that the bulk of the rounded pyrite is of detrital origin. Investigations, furthermore, suggested that the pyrite was formed also by pyritization of black sand constituents, by precipitation subsequent to the deposition of the conglomerates, and by mobilization and recrystallization during the metamorphism of the sediments.

The first comprehensive study of the Witwatersrand pyrite was carried out by Ramdohr (1958) who distinguished the following four groups of pyrite: (i) pebble pyrite, (ii) pyrite pseudomorphs, (iii) concretionary pyrite and (iv) "hydrothermal" pyrite. In all of these four groups, subgroups can be distinguished. This clearly demonstrates the considerable variation of the pyrite structures, and also indicates the difficulties encountered in interpreting their various modes of formation. For this reason, the present study cannot hope to provide a fully comprehensive description and explanation of all the occurring forms. The extensive sample material gathered for an ore-microscopical and geochemical investigation of the Basal Reef, from the Free State Geduld Mine, near Welkom, in the Orange Free State, exhibited interesting and hitherto undescribed pyrite structures. These include probable organic structures or "mineralized bacteria" which occur fairly abundantly throughout the reef and which are described in this paper. Pyrite forms previously observed and discussed by earlier investigators are also described, particularly where they exhibit a striking development or represent genetically important forms. This paper is, therefore, to a certain extent, a condensation of some of the more recent studies dealing with the Witwatersrand pyrite.

The various pyrite structures are best described and illustrated using photomicrographs. It is hoped that the comprehensive set of photographs accompanying this paper will provide for the geologists working on the Witwatersrand mines, and who rarely get the opportunity to study the ores with an ore-microscope, an indication of the numerous variations in development of the Witwatersrand pyrite —— a mineral that plays a somewhat neglected role when compared with the economically important gold and uraninite.

CLASSIFICATION OF THE DIFFERENT PYRITE TYPES

It is necessary to discuss briefly the classification of the numerous pyrite forms. The traditional grouping of the constituents of the Witwatersrand conglomerates, established by Young (1917), distinguished between allogenic and authigenic components. The first group comprises the original detrital components, introduced at the time of banket formation, while the second group is comprised of minerals formed within the banket, after its deposition.

Ramdohr (1958) was able to show that pyrite occurs among the allogenic as well as among the authigenic constituents of the conglomerates and that it is not solely an authigenic mineral, as maintained by Young (1917). The compact rounded pyrite grains are examples of allogenic constituents of the banket (see Plate 1, Figures 1, 2, 3, and 4), whereas the fine pyrite veinlets which often cut through other fractured minerals are authigenic constituents (see Plate 13, Figure 51). In many cases, however, the grouping of pyrite is not easy. The classification of pyritized black sand components into allogenic and authigenic constituents is impossible, since they might have been introduced into the banket in an already pyritized condition or, they might have been pyritized subsequent to their deposition within the banket. It is considered that both these modes of formation probably coexisted simultaneously. Further controversial pyrite forms include loose, distinctly rounded concretions, whose outlines are suggestive of transport, but whose delicate structures point towards an <u>in situ</u> formation (see Plate 4, Figure 16) and, redeposited pyrite of reworked older ore-horizons (see Plate 2, Figure 6, and Plate 13, Figure 50). For these reasons a descriptive classification of the Witwatersrand pyrite appears to be more practical and avoids all uncertainties as to the mineral genesis. It is clear that a descriptive classification will largely coincide with a grouping into allogenic and authigenic constituents, because the morphology of pyrite grains is essentially determined by its mode of formation.

The classification proposed by Ramdohr (1958) and mentioned earlier, has been modified accordingly and the following grouping of the Witwatersrand pyrite is used in this paper (see Table 1):

A. <u>Rounded Pyrite</u>

(a) compact rounded pyrite
(b) porous rounded pyrite
(c) rounded pyrite pseudomorphs
(d) concretionary pyrite
(e) pyrite nodules containing microspherical structures ("mineralized bacteria")

B. <u>Idiomorphic Pyrite</u>

(a) compact idiomorphic pyrite
(b) porous idiomorphic pyrite
(c) compact pyrite encrustations
(d) porous pyrite encrustations

C. <u>Xenomorphic Pyrite</u>

(a) pyrite veinlets and fracture fillings

TABLE I: DIFFERENT PYRITE STRUCTURES IN THE BASAL REEF

Morphology	Structures	allogenic	authigenic
rounded	compact or porous	detrital pyrite and black sands pyritized before their final deposition	black sands pyritized in situ
	pseudomorphic	inhomogeneous black sands pyritized before their final deposition	inhomogeneous black sands pyritized in situ
	concretionary		generally formed in situ; very rarely signs of short transportation
	mineralized bacteria		formed in situ; indicating presence of primitive life
idiomorphic	compact or porous		formed in situ by reconstitution of ferrous sulfide; rarely hydrothermal along dyke contacts
	compact or porous encrustations		formed in situ by reconstitution during metamorphism; generally overgrow older detrital pyrite
xenomorphic	veinlets and fracture fillings		formed in situ by reconstitution during metamorphism

The major proportion of the rounded pyrite has a grain-size of less than 2 mm. Larger pyrite grains are rather rare, and form a striking macroscopic constituent of the Witwatersrand ores. Following a suggestion made by Viljoen (1963 and 1967) the larger rounded pyrite grains have been further subdivided into two groups according to their diameters. These are referred to as "granular" or "buckshot" pyrite when possessing a diameter between 2 and 4 mm, and as "pebble" pyrite when having a diameter of more than 4 mm. (Buckshot pyrite is a term commonly used on the Witwatersrand mines for large, rounded, pyrite grains). A distinction is drawn here with the nomenclature of Ramdohr (1958), who frequently used the term "pebble pyrite" for a rounded detrital pyrite grain, disregarding entirely its grain-size. By doing so, he created considerable misunderstanding among most English speaking students of the Witwatersrand ores. The expression "pebble" was used by Ramdohr (1958) following his use of the German expression "Geroll" which refers to form and origin, but not to grain-size (see also Davidson, 1960 and 1961, and Ramdohr, 1961).

A. ROUNDED PYRITE

(a) Compact Rounded Pyrite

In all the polished sections studied from the Basal Reef the compact rounded pyrite very clearly forms the greatest percentage of all the rounded pyrite grains (see Plate 1, Figures 1, and 2). Its diameter is generally less than 2 mm and the compact rounded pyrite grains rarely reach the pebble grain-size.

Compact rounded pyrite grains are almost exclusively detrital components of the banket, originating initially from the primary ore deposits —— in many cases believed to be gold-quartz vein-deposits. This detrital pyrite entered the conglomerates in an exceptionally unweathered condition. Besides the waterworn shapes, "primary" inclusions of gold, whose colour is slightly whiter and whose reflectivity is measurably higher than that of the re-deposited and recrystallized gold in the ore-horizons, provide additional evidence in support of an allogenic origin for the rounded compact pyrite grains. The higher reflectivity of "primary" gold inclusions suggests a higher Ag-content and therefore indicates no re-crystallization of this gold (see Plate 1, Figure 3).

Other primary inclusions in rounded compact pyrite grains consist of pyrrhotite, pentlandite and chalcopyrite, the latter usually carrying exsolution discs of mackinawite (see Plate 1, Figure 4, and Plate 2, Figure 5). Further criteria suggesting a detrital mode of formation of the compact rounded pyrite grains in the Witwatersrand conglomerates have previously been outlined by several investigators, including Ramdohr (1958), Viljoen (1963 and 1967) and Schidlowski and Trurnit (1966). Frequently the cubic cleavage of the initially coarse pyrite crystals can be observed. During transportation of the detrital grains this cleavage has clearly influenced the present forms of the pyrite. In addition, the compact rounded pyrite grains are often found encrusted by younger, secondary pyrite, formed in situ. These pyrite overgrowths are often bounded by crystal faces, and in many cases camouflage the rounded pyrite cores to such an extent, that they can hardly be recognized (see Plate 2, Figures 6, 7, and 8, and Plate 3, Figure 9).

It is also extremely difficult, if not impossible, to distinguish between rounded pyrite of primary origin and rounded compact pyrite formed by pyritization of homogeneous black sand constituents such as magnetite or hematite. All these "pure" minerals rarely exhibit any relic structures when pyritized, and all possess the same waterworn morphology. In a few cases, however, it was possible to detect replacement relics of magnetite and hematite in rounded compact pyrite grains (Ramdohr, 1958, and Saager, 1968) (see Plate 3, Figure 10). This affords sufficient proof that pyritization of rounded black sand grains did in fact take place. It is suggested that a relatively large percentage of the rounded compact pyrite in the Basal Reef actually represents replaced detrital black sand grains, which cannot, however, be recognized as such, for the abovementioned reasons. This idea differs from that of Viljoen (1963 and 1967) who did not find replacement remnants of black sands in the pyrite from the Main Reef and Main Reef Leader. He therefore concluded, that the amount of black sand constituents must have been negligible, or entirely absent, in these reefs.

Schidlowski and Trurnit (1966) made a detailed study of indentations on pyrite produced, according to the Themse-Serby-Riecke principle, by pressure solution. They consider this common phenomenon, seen among the compact rounded pyrite grains of the Witwatersrand ores, to be strong evidence supporting their detrital origin (see Plate 1, Figure 2). The cataclasis of the rounded compact pyrite is extremely variable and it is odd that frequently the smaller grains are more shattered than the larger ones of even pebble size.

(b) Porous Rounded Pyrite

The porous rounded pyrite grains are far less common than the rounded compact grains and are sometimes difficult to distinguish from the loosely-knit pyrite concretions which occur abundantly in the portion of the ore deposit studied. Poorly prepared polished sections very often make it impossible to distinguish clearly between the different types of porous rounded pyrite grains. Thus, for this investigation only perfectly polished, pore-free sections were used. Where difficulty was experienced in differentiating between the porous rounded pyrite and the loose concretions the writer used the following criteria as guiding rules:

(i) Porous rounded pyrite is, in all cases, smaller than the loosely-knit concretions. The diameters seldom exceed 2 mm.

(ii) Porous rounded pyrite grains are usually less porous than concretions. Generally the pores in the porous rounded pyrite are filled to the grain centres with pyrrhotite, chalcopyrite, or sometimes with pentlandite and galena. These inclusions in the porous rounded pyrite represent associations of the primary ore deposits, whereas in the case of the concretionary pyrite, such inclusions were formed by infiltration of mobilized sulfides, and took place during the metamorphism of the conglomerates. This infiltration material, however, hardly ever advanced beyond the periphery of the concretions and thus it did not fill pores in the centre of the grains.

(iii) The most distinctive criterion, is the entire absence of delicate octahedral axial crosses in the porous rounded pyrite. These axial crosses are a very prominent feature in the loosely-knit concretions and are discussed later.

Most of the porous rounded pyrite grains are also considered to be detritogenic. They appear to be a variety of the compact rounded pyrite type which possessed a far greater number of pores and inclusions, but which occurred less frequently in the primary ore-bodies. Because the filling of the pores by gangue and ore-minerals, resulting in increased physical strength of the material, took place in the primary deposit, prolonged transportation of the grains without disintegration can be readily accepted. This differs from the concretionary pyrite which always has a more fragile structure and which, in spite of its rounded outlines, could only have been transported over very short distances, if it had been transported at all (see Plate 5, Figures 17 and 18). This, to a certain extent, might also be a reason for the larger grain-size of the concretions. Some of the porous rounded pyrite may also originally have been black sand constituents. An authigenic formation of some of the porous rounded pyrite cannot, therefore, be excluded.

(c) Rounded Pyrite Pseudomorphs

The rounded pseudomorphic pyrite grains represent pyritized iron-rich minerals.

These still exhibit relics of their former structures and compositions and can therefore, clearly be identified as pseudomorphs. These pseudomorphs must have entered the conglomerates in an already pyritized condition or else they were pyritized in the basin of sedimentation very shortly after their deposition. Distinguishing between the two modes and times of pyritization appears to be impossible. Ramdohr (1958) believed that a substantial proportion of the rounded pyrite pseudomorphs were already pyritized when they entered the conglomerates and that they must, therefore, be considered as allogenic constituents of the Witwatersrand ores. The possible occurrence of organic life in the basin of deposition of the Basal Reef, as discussed later in this paper, suggest however, that the sulfur which was necessary for the pyritization of the pseudomorphs could have been derived from biological processes, which took place within the basin of sedimentation. Thus it is proposed that for the Basal Reef, a substantial amount of the black sands and other iron-rich detrital matter were pyritized within the banket.

It has been mentioned earlier that homogeneous iron-rich minerals infrequently show any relic structures and therefore, they cannot be distinguished from "primary" pyrite. For this reason they were discussed in the two preceeding sections of this paper.

The recognition of rounded pyrite grains, pseudomorphous after titaniferous magnetite or limonite, is in all cases very simple. The structures resulting from these minerals are discussed in great detail by Ramdohr (1958). This obviates the need for further discussion in this paper. However, some very instructive examples encountered in this study are illustrated with photomicrographs (see Plate 3, Figure 12, and Plate 4, Figures 13 and 14).

A large number of rounded pyrite pseudomorphs after limonite, itabirite, oolites, iron-quartzites, specularite schists and banded ironstones were observed in the Basal Reef (see Plate 3, Figure 11). Some of these pseudomorphic structures are hardly distinguishable from concretions and "mineralized bacteria". All the spherical to sub-spherical microstructures are therefore discussed in the two following paragraphs.

(d) <u>Concretionary Pyrite</u>

Concretionary pyrite forms by far the largest proportion of the granular-, buckshot-, and pebble-size pyrite. In spite of their generally loose and delicate forms the concretions have distinctly rounded outlines (see Plate 4, Figures 15 and 16, and Plate 5, Figures 17, 18, and 19). This would appear to be suggestive of some transport of the material. The fragility and the general absence of cataclasis, however, is evidence against any long transportation. Thus, it is considered that some of the almost perfectly rounded individuals represent actual concretionary structures, the shape of which cannot be used as an indication of abrasion during transport (see Plate 5, Figures 17 and 18).

Skeletal-type growth structures (e.g. delicate axial crosses) are found in practically all pyrite concretions. The presence of these skeletal structures can therefore be used to distinguish the concretionary pyrite from the pyrite pseudomorphs and the rounded porous pyrite (see Plate 5, Figure 20, and Plate 6, Figures 21 and 22). Ramdohr (1958) suggested that the concretions grew from single nuclei, forming firstly, very loose, delicate structures, that were gradually converted to compact aggregates, provided sufficient material was available. Even in these compact aggregates the octahedral axial crosses can be made visible by etching the grain for 30 to 90 seconds with concentrated HNO_3 (see Plate 6, Figures 21 and 22). Frequently the concretions were found to have a compact core and a more porous and delicate rim. This probably indicates that during the growth of these concretions less material became available to form a completely compact aggregate.

It was found that the concretionary pyrite aggregates very often consist of an isotropic and an anisotropic pyrite variety (see Plate 6, Figure 23). These two types of pyrite were found intimately intergrown with each other and when closely examined, showed a different hardness and reflectivity. Saager and Mihálik (1967) described this phenomena in detail and showed that the two pyrite varieties have a markedly different trace element content of As, Co and Ni, and therefore possess different optical properties. The very delicate structures of the pyrite aggregates, showing the two pyrite varieties, suggest either, an in situ formation or, short transport distances. Saager and Mihálik (1967) accordingly propose "a formation from Fe-rich silica gels by the addition of H_2S". In a similar manner to the porous pyrite grains, the concretionary pyrite acted as a trap for metamorphically mobilized gold and base metal sulfides, which infiltrated into the pores of the marginal areas, where they now form inclusions. This association of concretionary pyrite, gold and base metal sulfides clearly illustrates that the formation of the concretions took place prior to the mobilization of the gold and the base metal sulfides. Thus the concretions must have formed before the metamorphic period, probably very shortly after the deposition of the sediments.

Ramdohr (1958) has described the different forms of concretionary pyrite and their modes of formation in great detail. Since the concretions encountered in the Basal Reef exhibit the same forms as those described by Ramdohr, further discussion is unnecessary. The subdivision of the concretionary pyrite into three groups used by Ramdohr (1958) was, however, found to be impracticable in the Basal Reef and was therefore not employed in this study.

(e) Pyrite Nodules Containing Microspherical Structures ("Mineralized Bacteria")

Delicate pyrite aggregates exhibit at times complex microspherical structures of the "mineralized bacteria" type. They generally reach diameters of 10 to 15 microns, but have been observed as large as 45 microns. In most cases these microspheres were irregularly distributed in the rounded pyrite masses. For a detailed presentation of numerous forms of "mineralized bacteria" the reader is referred to the photomicrographs (see Plate 6, Figure 24; Plate 7, Figures 25 to 28; Plate 8, Figures 29 to 32; Plate 9, Figures 33 to 36; and Plate 10, Figures 37 and 38).

The occurrence of spheric to subspheric structures in the Witwatersrand ores has been already reported by Ramdohr (1958) who stated: "These 'small oolites' are of the same dimension and have the same properties as the so-called 'mineralized bacteria' of pyrite and could thus be a primary deposition in themselves if the compact pyrite matrix was not present, which in such formations is quite new to me". With reservation, Ramdohr (1958) considered some of these structures to be limonite ores which were already pyritized in their primary deposits. He points also to the possibility, however, that similar structures could be attributed to the activity of H_2S generating black-mud bacteria.

Substantially larger, and slightly different, concentric and oolitic pyrite structures are also described from the Ventersdorp Contact Reef by von Rahden and Schweigart (1964). They postulated that these structures are oolitic and believe "that a causative connection has existed between primitive organic life and the formation of these oolites and related textures". Their explanation differs from that of Davies (1949) who interpreted the same structures as replacements of rounded quartz grains by pyrite.

A more recent description of possible life forms from the Elsburg Reef in the Orange Free State Goldfield has been presented by Schidlowski (1963 and 1965). He distinguished two types of microstructures: "Type 1 forms spherical to subspherical granules consisting of a central core-body enveloped in an outer ring, suggesting the presence of an external sac. The granules occur as isolated spots in the pyrite, only in a few cases are individuals seen to touch each other. They measure from 5 to 21 microns.

Type 2 is represented by spherical to elliptical globules surrounded by double layered walls, each of the constituting layers appearing as a delicate stippled line. These elements are somewhat smaller than those of type 1 : they are between 4 microns and 16 microns across; their average ranging from 7 to 11 microns. In contrast to type 1, these forms very often tend to aggregate in clusters resembling globose colonies".

Of all probable life forms described from the Witwatersrand ores, the microstructures presented by Schidlowski (1963 and 1965) from the Elsburg Reef resemble most, the forms found by the present author in the Basal Reef (see Plate 7, Figures 25 and 26, and Plate 9, Figures 33 and 34). From the literature dealing with possible organic structures in the Witwatersrand ores, it appears that the "mineralized bacteria" are an exceptionally abundant and, therefore, significant constituent, in the Basal Reef of the Free State Geduld area. They are thus dealt with more fully. The unusual fact that the detrital pyrite grains do not exhibit any marked weathering, coupled with the presence of uraninite, which commonly decomposes quickly during transport and is thus not concentrated in placer deposits, is suggestive of reducing conditions having prevailed in the sedimentational environment of the Witwatersrand conglomerates. If the observed microspheres are actually organic structures their environment must have been of a reducing nature. This is an environment in which sulfate reducing and sulfide producing bacteria occur, since they are anaerobic and unable to grow in the presence of dissolved oxygen. These microbes oxidize hydrogen to water, using sulfate as the source of oxygen and produce sulfide as a by-product. The formula for this reaction is given by Temple (1964)

$$SO_4^{--} + 8\,H \rightarrow 4\,H_2O + S^{--} + \text{energy}$$

Ideal conditions for anaerobic H_2S producing organisms are encountered in basins where the exchange of oxygen with the air is limited or the consumption of oxygen is great. Such conditions are found in the sapropels of river bed fillings, poorly aerated lagoons, or truncated estuaries, as well as in tidal flats and in the bottom muds of well-aerated basins, and could quite possibly have occurred in the sedimentation basin of the Witwatersrand conglomerates just after their deposition.

In reducing sulfates, and producing H_2S by biochemical reaction, the anaerobic microbes have played an active part in the precipitation of ferrous sulfide from iron in solution, and therefore, in the formation of the concretionary pyrite and pseudomorphic pyrite. It is further possible that part of the metamorphically mobilized and recrystallized pyrite and other metal sulfides were originally biogenically precipitated sulfides. This provides an explanation for the formation of some of the mobilized sulfides in the Witwatersrand ores and also for the distinctly selective mobilization of the pyrite. The compact rounded pyrite was to a large extent resistant to the mobilization, in contrast to the precipitated, probably amorphous, iron sulfide aggregates which were mobilized and reconstituted as idiomorphic secondary pyrite.

Love and Zimmerman (1961) regarded it as very unlikely that the microorganisms would have played a passive role, inducing a catalytic reaction between iron and sulfide ions. It is also regarded as unlikely that the chemical composition of the microorganisms was such that they precipitated sulfides on decay. The quantity of organisms, these investigators maintained, could hardly have been sufficient for the volume of metal-sulfide produced. Rubenchick (1946) stated that in the Black Sea 99.4 to 99.6 per cent of the total amount of H_2S was formed as the result of the activity of sulfate reducing bacteria. Fixation of H_2S as metal sulfide is further important to guarantee the survival of such bacteria colonies since high concentrations of molecular H_2S is toxic to sulfate reducing bacteria (Rubenchick, 1946, and Love and Zimmerman, 1961).

The preservation of non-skeletal micro-organisms is very rare and all sulfate reducing micro-organisms can be expected to decay very rapidly. However, Temple (1964) stated : "Bacterial remains in sediments are a possibility if there is rapid sedimentation in an anaerobic environment. Such cells could be pyritized but it would be almost impossible to identify the organisms". This fact clearly explains the difficulties encountered when dealing with "mineralized bacteria" and is also a reason for the controversies which surround this subject. The nature of the original ferrous sulfide is uncertain. Love and Zimmerman (1961), believe that it occurs in an amorphous form. Rubenchick (1964) found in Sporovibrio, that the iron sulfide is probably changed within the cells of the organisms firstly, into melnikovite pyrite, and then into pyrite.

For all these reasons it seems quite possible that the spheric to subspheric structures found in pyrite nodules in the Basal Reef represent life forms. The fact, however, that exactly similar spherical forms are encountered in undoubted hydrothermal ore bodies makes the interpretation of these structures more difficult (Ramdohr, 1960). They cannot, therefore, be interpreted only by their form and structure; genetical aspects of the ore deposits other than those concerning the pyrite must also be considered.

Snyman (1965) who investigated the thucholite of the Witwatersrand conglomerates by means of new coal-petrographic techniques, encountered forms similar to algal structures found in sapropelic coal. He concluded that thucholite could well represent a high-rank sapropelic coal. The comparison of analytical values of thucholite with values of sapropelic coal based on a dry, ash-free, basis shows rather good agreement except for the low hydrogen content in the thucholite. This Snyman (1965) explains as a dehydrogenation : "The bombardment of the sapropel by alpha particles led to pronounced dehydrogenation of the organic material and brought about structural changes analogous to an increase in rank".

Liebenberg (1955) also suggested : "One of the most feasible sources of the methane and sulphuretted hydrogen, the latter gas being instrumental in the conversion of iron-bearing minerals to pyrite, appears to be organic remains, which were probably present and in various stages of decomposition, in the water of the wide depositional basin in which the Witwatersrand sediments were laid down. The increase in the amount of hydrocarbonaceous material in the various systems when followed upwards from the Dominion Reef to the Black Reef must thus suggest the gradual development of organic life". Liebenberg (1955) explained the formation of thucholite as a polymerization of hydrocarbonaceous substances by radioactive emanations from uraninite, shortly after the deposition, and prior to the consolidation, of the banket.

Both these theories differ from the interpretations put forward by Davidson and Bowie (1951), who believed that the gaseous hydrocarbons originated from the coal seams of the Karroo. It is, however, not easy to visualize a downward migration of methane, a gas which would certainly tend to travel upwards, away from the Witwatersrand sediments. In addition, the intergrowth structures between thucholite, gold and pyrrhotite suggest a very early appearance of the thucholite in the banket. Ramdohr (1958) also believed that the thucholite came into the conglomerates at a very early stage. He stated : "Whether one has in mind bacteria that already existed during the time of the Witwatersrand, in line with the ideas of the 'precipitationists' or whether one thinks of the exhalations from the Ventersdorp lava, decisive criteria for these have not been found".

Since Barghoorn and Schopf (1966) and Pflug (1966) have described micro-organisms in rocks older than 3200 million years from the Fig Tree Series (Nicolaysen, 1962), the existence of life during the deposition of the younger sediments of the Witwatersrand System can no longer be disputed.

A factor against a biogenic origin of the sulfides has been brought forward by Jensen and Dechow (1964) who investigated 40 sulfides from the Vaal Reef at the Hartebeestfontein mine. They could not find any sign of bacterial fractionation of sulfur isotopes, which strongly suggests a magmatic hydrothermal origin of the sulfur. Since the concretionary pyrite and the "mineralized bacteria" form only an extremely minor and irregularly distributed portion of the Witwatersrand pyrite, and because they are very difficult to isolate and concentrate, the author feels that the isotope ratios obtained by Jensen and Dechow (1964) might have been affected by sampling methods.

Considering all the above investigations the writer believes that, with due reserve, it can be reasonably assumed that the microspherular structures in pyrite aggregates of the Basal Reef very likely represent micro-organisms of some type, which decayed in an anaerobic environment. In such anaerobic, toxic conditions, with oxygen entirely lacking, sulfate reducing organisms exist and act as H_2S generators. This explanation is not only in agreement with the presence of carbonaceous matter in the ore body, but also gives a simple explanation of the source of H_2S. Furthermore, it provides an explanation for the reducing environment which existed in the sedimentation basin. The relative scarcity of spheric to subspheric pyrite structures, as well as the irregular distribution of pyrite concretions and mobilized pyrite, seems to indicate that the anaerobic conditions did not prevail over the entire basin during its entire history, but existed for short periods, just after deposition in small pocket-like areas. Such anaerobic pockets appear to have been somewhat more abundant in the sedimentation area of the Basal Reef of the Free State Geduld Mine, where "mineralized bacteria" and pyrite concretions were more frequently observed than in other areas of the Witwatersrand Goldfield.

H_2S not only precipitated iron which was in solution in the basin but was also responsible for the formation of the pyrite pseudomorphs (black sands) which were pyritized in situ; this is in accordance with Temple (1964), who stated : "It is evident that not only soluble metal salts but also many relatively insoluble oxides, carbonates and silicates can be converted to sulfide in the presence of a sulfate-reducing culture at atmospheric pressure and room temperature".

B. IDIOMORPHIC PYRITE

(a) Compact Idiomorphic Pyrite

The idiomorphic compact pyrite grains are considered to be authigenic constituents of the banket because of their crystal outlines. The only exceptions occur when rounded detrital grains are encrusted by in situ overgrowths of pyrite with crystallographic forms, which can completely camouflage the detrital cores (see Plate 3, Figure 9). Such aggregates can, therefore, erroneously be interpreted as authigenic grains, yet they possess an allogenic core and an authigenic rim. The compact idiomorphic pyrite grains cover an extremely wide size range which extends from below 10 microns to more than 2 mm. Two varieties of differing origin were distinguished in the Basal Reef.

(i) The first variety consists of idiomorphic compact pyrite grains which were formed by mobilization and recrystallization during the metamorphism of the Witwatersrand sediments (see Plate 1, Figure 1). They were formed under pseudohydrothermal conditions, since the redeposition must have taken place under relatively high temperatures and pressures with the main transporting agent most likely being water. In many polished sections this type of idiomorphic pyrite was found to be more abundant than the rounded detrital pyrite. Ramdohr (1958) suggested a more or less contemporaneous redeposition of the gold and idiomorphic pseudohydrothermal pyrite. The mineragraphic observations made by the present writer confirms this interpretation. It is quite striking that the idiomorphic compact pyrite very rarely exhibits infiltrations of gold and base metal sulfides. This is in contrast with the detrital rounded pyrite and the pyrite pseudomorphs and concretions. Where the secondary, remobilized pyrite surrounds "older" detrital minerals no replacement, or only limited peripheral corrosion, could be observed (see Plate 12, Figures 45 and 46). The possible derivation of the remobilized pyrite from precipitated amorphous ferrous sulfide has been discussed in the preceeding paragraph.

The occurrence of radioactive corrosion phenomena and blasting haloes in idiomorphic pyrite grains has been discussed in detail by Schidlowski (1966). He suggested that the strong alpha radiation emanating from the uraninite inclusions in the authigenic pyrite cubes destroyed the lattice and thus caused the formation of radial expansion cracks in the pyrite. He found similar phenomena with inclusions of other radioactive minerals. The radiogenic corrosion of pyrite in juxtaposition with uraninite is also caused by the bombardment of alpha radiation. The part of the lattice which is exposed to the radiation becomes unstable and is eventually leached away by percolating solutions (Ramdohr, 1957). Frequently a thin rim of pyrrhotite was observed in the radiogenic embayments (see Plate 10, Figure 39). Schidlowski (1966) who noted the same phenomena, commented on it as follows: "If situated in pyrite, the radioactive mineral may sometimes be shielded off from the latter by a seam of newly formed pyrrhotite". Schidlowski gives no explanation as to the origin of the pyrrhotite and it is not known whether or not he postulated pyrrhotite formed by sulfur-substitution, caused by alpha bombardment, or if he postulated a simple infiltration of mobilized pyrrhotite into the newly formed "open" cavities. The writer favours a radiogenic sulfur-substitution since the pyrrhotite rims were also observed in samples which were entirely free of any other pyrrhotite aggregates. Further evidence against a redeposition of mobilized pyrrhotite in the radiogenic cavities is the complete lack of chalcopyrite, galena, or gold, in these corrosion embayments. All these minerals, which occur in the reef, are just as easily mobilized as pyrrhotite. It is interesting to note that radioactive corrosions and blasting haloes, as well as the pyrrhotite seams in radiogenic cavities are not a common phenomena and were found only in a few polished sections (see Plate 12, Figures 45 and 46).

(ii) The other type of compact idiomorphic pyrite is a "true" hydrothermally formed variety, produced as a result of the intrusion of dykes into the Basal Reef during Ventersdorp times (see Plate 10, Figure 40, and Plate 11, Figure 41). Similar hydrothermal mineralization has been explained in detail by Saager (1968) who discussed the presence of proustite and stromeyerite in the Basal Reef, where these minerals occur in enriched masses of galena, sphalerite, and chalcopyrite, along the contact of an intrusive dyke. The idiomorphic hydrothermal pyrite crystals occur as relatively small inclusions in the abovementioned base metal sulfide enrichments and are strongly replaced by the surrounding sulfides. It is normally an easy task to distinguish between the pseudo-hydrothermal and the hydrothermal compact idiomorphic pyrite, since the latter type occurs only in the contact zones of intrusive dykes. Here it occurs together with other hydro-thermal minerals, particularly galena, chalcopyrite, and sphalerite, all of which form en-richments and generally replace the earlier emplaced pyrite cubes.

Frequently, masses of compact or porous, idiomorphic pyrite have been found intimately intergrown with similarly developed marcasite (see Plate 11, Figures 43 and 44). In such cases, the two minerals could only be readily distinguished when observed under crossed nicols. The occurrence of such intergrowths suggests a relatively late formation of the marcasite, possibly under rather low temperatures. In this connection, the occurrence of flack- and table-shaped mackinawite (tetragonal $(Fe, Ni, Co)_{1+x}S$) should be mentioned. In a few cases this was found as an overgrowth on the pyrite-marcasite assemblages, usually accompanied by some pyrrhotite (see Plate 11, Figure 42). Identical occurrences of mackinawite in the Witwatersrand ores were first described by Schidlowski and Ottemann (1966). Borchert (1934) suggested a formation temperature of valleriite (mackinawite) of 225^{o} to 250^{o}C. Accordingly, Schidlowski and Ottemann (1966) concluded that at least similarly high temperatures must have been reached during the metamorphism of the Witwatersrand sediments, and that this led to the pseudohydro-thermal mineralization of the secondary sulfides. This suggestion, however, is somewhat invalidated by the experiments of Berner (1962) who was able to synthesize mackinawite from aqueous solutions at room temperature and atmospheric pressure in a strongly reducing environment, and also by the observations of Clark (1966), who suggested that the upper stability limit of mackinawite is directly influenced by its Ni and Co contents. For the Co- and Ni-free end-member $Fe_{1+x}S$, Clark (1966) proposed a stability limit of 135°C. This temperature seems to the writer a far more reliable minimal temperature attained by the sediments during their metamorphic stage.

(b) Porous Idiomorphic Pyrite

The porous idiomorphic pyrite grains have to be interpreted genetically in the same manner as the compact idiomorphic pyrite. Thus, this variety was formed by pseudohydrothermal mineralization during metamorphism. Very often transitions can be observed from compact pyrite into porous idiomorphic pyrite (see Plate 12, Figures 47 and 48). The numerous pores are generally developed in distinctive crystallographic directions and zonal arrangements. This differs markedly from the pores which occur in the concretionary pyrite and in the pyrite pseudomorphs where pores are randomly distributed, and show no zonal arrangement in crystallographic directions (see Plate 12, Figure 47; Plate 13, Figures 49 and 50; and Plate 4, Figures 15 and 16). Ramdohr (1958) suggested that the porous idiomorphic pyrite was formed later than the compact idiomorphic type and that it must have grown quickly. This is because the formation of many coarse, usually rounded pores, all of the same size, and with conspicuous zonal arrangement, is incompatible with slow growth. The later formation of the porous idiomorphic pyrite is also borne out by the appearance of pyrite idioblasts having compact cores which slowly grade outwards into more porous rims (see Plate 12, Figure 47).

The extremely delicate structures and the distinctive cubic outlines of the idiomorphic pyrite grains are sufficient proof for absence of transport, and is furthermore evidence for suggesting an in situ formation within the banket. Inclusions of metamorphically mobilized minerals such as gold and chalcopyrite, which commonly occur in other porous pyrite grains, have only been found infrequently in the idiomorphic porous pyrite. This indicates that this pyrite type crystallized even later than the gold and the chalcopyrite. Generally the amount of porous idiomorphic pyrite was found to be less than that of compact idiomorphic pyrite. Usually, however, the porous idiomorphic pyrites possess a larger grain-size than the latter variety, which can be attributed to their faster growth rate.

(c) Compact Pyrite Encrustations

In principle, the pyrite encrustations on other pyrite grains are exactly the same as the pyrite idioblasts. They were also mobilized during the metamorphic period, which took place as a result of the superposition of thick successions of sediments and lavas, and grew on other detrital constituents of the banket, particularly on rounded compact pyrite (see Plate 1, Figure 4, and Plate 3, Figure 9). The overgrowths, as mentioned earlier, are generally in crystal forms making it very difficult to recognize the abraded cores. Such aggregates, however, usually show a far larger grain-size than the common compact idiomorphic pyrite. It has been found that etching with concentrated HNO_3 reveals, in many cases, the detrital core (see Plate 2, Figures 7 and 8). In a few instances, the zone of instability between the older core and younger overgrowth could also be recognized by a distinct line of pores, or by a fine film of other sulfides (see Plate 3, Figure 9).

(d) Porous Pyrite Encrustations

This pyrite variety must have formed in a manner analogous to the compact encrustations but, due to the numerous pores arranged in distinct crystallographic zones, it is easier to recognize, especially when the encrustations overgrow a compact core (see Plate 2, Figure 7, and Plate 12, Figure 48). In the Basal Reef the porous encrustations have also been found, in a number of instances, to overgrow allogenic conglomerate constituents other than pyrite.

C. XENOMORPHIC PYRITE

(a) Pyrite Veinlets and Fracture Fillings

The abovementioned late pyrite encrustations lead directly to the common stringer-like pyrite veinlets which cut through fractured allogenic minerals and form fracture fillings in other minerals (see Plate 13, Figure 51). Crystal forms are generally absent. The occurrence, and the development of this vein-pyrite, suggests a very late formation, possibly later than that of the encrustations. The vein-pyrite mineralization is also caused by pseudohydrothermal mobilization, and subsequent deposition. Viljoen (1963 and 1967), considered that the extremely thin (sometimes only 2 microns thick) pyrite veinlets are an indication of the exceptionally mobile nature of the pyrite redeposited during the metamorphic stage.

CONCLUSIONS

This study of the pyrite from the Basal Reef of the Free State Geduld Mine at Welkom, in the Orange Free State Goldfield, clearly reveals the necessity for a suitable and comprehensive classification of the various forms encountered. This has resulted in a modification of the grouping employed by Ramdohr (1958). For the classification, use has been made of the morphology of the different pyrite structures (see Table 1, page 3). This essentially descriptive classification, eludes genetical issues. In other words, allogenic as well as authigenic pyrite grains may be placed in the same group if they possess similar structures and outlines. This is the case, for example, with rounded detrital grains of pyrite and rounded in situ pyritized black sand constituents.

According to the sedimentological classification of Wentworth (1962), rounded pyrite grains with diameters of 2 to 4 mm have been given the prefix "granular" or "buckshot", and rounded grains with diameters of more than 4 mm have the prefix "pebble". This was done to obviate many of the misunderstandings which were created in the Witwatersrand literature by the introduction of the term "pebble" for any rounded pyrite, irrespective of its size, by Ramdohr (1958). Pyrite was found as rounded compact or porous detrital constituents, as pseudomorphs of former black sands and as concretionary aggregates, some of which exhibited spherical to subspherical micro-structures of the "mineralized bacteria" type. The pyrite, furthermore, occurs as remobilized and recrystallized idioblasts, encrustations and stringer-like veinlets, and finally it rarely forms "true" hydrothermally emplaced crystals.

The different pyrite structures occurring in the Basal Reef reveal that the ore deposit must have been formed by a great number of genetically different ore-forming events. This polygenetic nature of the ore explains not only the wide range of different pyrite structures but also the complex variety of ore-minerals. In the Basal Reef approximately 40 different ore-minerals have been reported (Saager, 1968).

The establishment of a detailed age sequence of the various types of pyrite which have been developed at various times was not attempted, because it would be very difficult to propose a succession which would satisfy all varieties of pyrite (Ramdohr, 1958). However, it can be envisaged that the waterworn detrital pyrite represents the oldest generation, followed by the pseudomorphic pyrite, the concretionary pyrite and the biogenically precipitated pyrite. After the consolidation and during the metamorphism of the Witwatersrand conglomerates the pseudohydrothermal compact pyrite idioblasts and encrustations were formed. These were followed, in turn, by the similarly formed porous idiomorphic pyrite encrustations, and eventually by the pyrite veinlets and stringers. The "true" hydrothermal pyrite cubes can possibly be regarded as the youngest pyrite generation. Most of the typical forms of pyrite found in the Witwatersrand sediments fall into this very generallized sequence of events.

Prominent in the Basal Reef is the occurrence of an exceptionally large amount of probable life forms of the "mineralized bacteria" type in the samples studied. This led the author to the conclusion that some of the sulfides present in the sediment were formed by the activity of anaerobic H_2S producing sulfate reducing micro-organisms. The presence of H_2S in the Witwatersrand basin, during the accumulation of the sediments, is regarded by most recent investigators of the ore deposit as necessary for the formation of the concretions and for the pyritization of the black sand constituents. Sources of H_2S other than those produced by bacteria could include subaqueous volcanic emanations or thermal springs which extruded into the basin. Signs of hydrothermal activity in the Witwatersrand sequence, however, are rare. The Jeppestown amygdaloid in the lower Witwatersrand formation and the Bird amygdaloid in the upper Witwatersrand formation may represent possible exceptions. It therefore seems reasonable to explain the larger proportion of the H_2S present in the basin as having been produced by biogenic processes. The presence of H_2S in the water led to a precipitation of metal in solution. Thus some of the other metal sulfides, as well as some of the pyrite might be explained as products of precipitation. This furthermore suggests a simple explanation for the occurrence of mobilized (idiomorphic, secondary) pyrite and unmobilized (rounded, detrital) pyrite next to each other in the Witwatersrand ores. The precipitated amorphous ferrous sulfide (Rubenchick, 1946) appears to have been relatively easy to mobilize and it might therefore be the source of the redeposited secondary pyrite. The detrital pyrite, on the other hand, was only little or not at all affected by the pseudohydrothermal conditions during the metamorphic alteration of the sediments. It was not mobilized and still displays its abraded and rounded outlines.

The theory suggesting that anaerobic life existed in the sedimentary basin is furthermore supported by the following criteria:

(i) The discovery of micro-organisms in much older rocks of the Fig Tree Series by Barghoorn and Schopf (1966) and by Pflug (1966).

(ii) Sulfate reduction by some biological agent is considered as one of the most primitive biochemical mechanisms (Temple, 1964).

(iii) The supposition by Temple (1964) that sulfate reducing microbes belong to the earliest organisms and,

(iv) The detection of algal-like forms in thucholite from the Witwatersrand sediments.

The occurrence of possible biogenic structures in the carbonaceous matter of the Witwatersrand ores is of importance, because the algae, on decay, could have provided the necessary organic compounds which some of the sulfate reducing bacteria require to produce H_2S. The decomposition of organic matter furthermore results in a high oxygen consumption, producing an environment conducive to the development of anaerobic life. Recent studied by Pretorius (personal communication) on various aspects on the Witwatersrand gold bearing reefs have shown that a particular reef horizon can be divided into a number of different parts according to the energy-level of deposition. It is thus clear that some portions of one reef horizon might develop in a fluviatile as well as in a lagoonal and marine type of environment. Sulfate reducing bacteria can exist in all these environments provided a depletion of oxygen took place during a period of quiescence.

The writer therefore believes that it can be reasonably assumed that anaerobic, reducing conditions prevailed in the Witwatersrand basin shortly after the deposition of the conglomerates, during a quiet period. An example of such an environment would be a badly aerated lagoon or a landlocked estuary. That the anaerobic environment existed only in relatively small areas and not over the entire basin of sedimentation is borne out by the fact that "mineralized bacteria" pyrite pseudomorphs and concretions, as well as carbonaceous matter, are not uniformly distributed in the different ore horizons or areas of the Witwatersrand basin. The relative abundance of these forms encountered in the particular localities of the Basal Reef examined points to the existence of an anaerobic pocket in the Free State Geduld area. The reducing conditions which occur in anaerobic basins are one reason for the unweathered appearance of the waterworn detrital pyrite in the Witwatersrand ores.

Finally, the writer wishes to stress that the small size and scarcity of the microspheres precluded further investigations other than visual observations under the ore-microscope. Comparisons could, however, be made with examples from the extensive literature dealing with these possible life-forms. All conclusions reached in this paper on these microspherical structures are therefore made with due reservation and should be viewed with necessary caution.

* *

APPENDIX

Two recently published papers which seem to underline the presence of algal and bacterial life in the Witwatersrand basin came to the attention of the author after completion of the manuscript.

Hoefs and Schidlowski (1967) investigated the stable carbon isotopes of seven thucholite samples from various auriferous reef horizons in the Witwatersrand System. They obtained $\delta\, C^{13}$ values between -22.4 and -32.8 per thousand. This falls into the range of organic carbon. Hoefs and Schidlowski concluded, therefore, that photosynthesis existed during the time of deposition of the Witwatersrand sediments and that primitive life flourished in the depositional basin of the Witwatersrand conglomerates.

Prashnowsky and Schidlowski (1967) demonstrated the presence of amino-acids and monosaccharides in carbonaceous material from the Basal Reef and the "B" Reef of the Orange Free State Goldfield. Prashnowsky and Schidlowski maintain that the presence of these amino-acids and monosaccharides can only be explained if life processes operated during the time of the sedimentation of the Witwatersrand conglomerates. They consider an abiotical formation of the amino-acids and monosaccharides as highly unlikely. Electron-micrographs taken of surface replicas of quartzites originating from near carbon bearing reefs, revealed cell-like structures and aggregates resembling cell-colonies. This, according to Prashnowsky and Schidlowski, provides a further indication of a possible organic derivation of the Witwatersrand thucholite.

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KEY TO PLATES

PLATE 1

Figure 1 : Typical section from the Basal Reef with a relatively high concentration of rounded compact and porous pyrite grains, as well as numerous authigenic idiomorphic pyrite crystals which were remobilized during the metamorphism of the sediments. The authigenic pyrite is clearly moulded around the immobilized "older" detrital pyrite. The dark grey rounded grain in the upper half of the photograph is detrital chromite. Note the identical form and the similar grain-size of the detrital chromite and pyrite. Magnification 100x, dry.

Figure 2 : Rounded detrital pyrite grains showing strong cataclastic shattering. Note the somewhat larger pyrite concretion in the centre which underwent no fracturing at all in spite of its larger diameter and relatively delicate structure. Some pyrite grains exhibit faint indications of pressure solution at their contacts. In the upper left corner, part of a large concretionary pyrite nodule can be seen.
Magnification 100x, dry.

Figure 3 : Rounded compact pyrite grains. The detrital pyrite in the centre has inclusions of gangue (black) and gold (white). This gold has not migrated into the pyrite. It has a slightly higher reflectivity, due to a higher silver content than the redeposited gold in the reef. It can be assumed that the gold, as well as the surrounding pyrite, are of primary origin, and represent an original assemblage of the source ore deposit, which probably was a gold-quartz vein.
Magnification 350x, oil immersion.

Figure 4 : In the centre, a rounded detrital pyrite grain with inclusions of gangue (black), chalcopyrite (slightly darker and distinctly softer than pyrite) and pyrrhotite (grey). These inclusions have not infiltrated into the pyrite but were present in the pyrite in the primary ore deposit. The crystallographic outlines of the pyrite grain, particularly along the upper part of the grain, are formed by a late in situ overgrowth of compact pyrite.
Magnification 350x, oil immersion.

PLATE 2

Figure 5 : Rounded compact pyrite grain with inclusions of gangue (black) and a distinctly bent molybdenite flake (grey). This primary assemblage indicates that some of the detrital pyrite constituents of the Witwatersrand ores might originate from pegmatitic-pneumatolytic ore deposits.
Magnification 350x, oil immersion.

Figure 6 : Part of a pebble-sized, distinctly abraded, pyrite nodule etched with concentrated HNO_3. This nodule possibly represents a fragment of an older ore-horizon which has been eroded, and the fragment reworked, rounded and redeposited in the Basal Reef. The etching clearly reveals the compact rounded pyrite grains. These etch out weakly, in contrast to the matrix of secondary pyrite. The reconstituted pyrite matrix contains in places small amounts of chalcopyrite and pyrrhotite. Before etching the entire nodule resembled a large concretionary pyrite grain and its true nature was unrecognizable.
Magnification 200x, dry.

Figure 7 : Three compact detrital pyrite grains encrusted by secondary reconstituted pyrite which grew in distinct crystallographic directions. In the upper left corner can be seen a large pyrite nodule, possessing the typical loosely knit structure.
Magnification 350x, oil immersion.

Figure 8 : Same section as in Figure 7, but etched with concentrated HNO_3 for 120 seconds. The porous encrustations, as well as the loosely knit pyrite nodule, have been strongly attacked, and were partly etched away. The strong but variable etching of the compact rounded pyrite grains is attributed to different crystallographic orientation of the three grains. Magnification 350x, oil immersion.

PLATE 3

Figure 9 : Detrital rounded pyrite grain encrusted by a pyrite overgrowth which developed crystal forms. This imparts to the aggregate the shape of an idiomorphic crystal. The zone of instability between the older, detrital core and the younger, authigenic encrustation is clearly marked by a thin line of pores thereby making it possible to recognize the complex association. Magnification 350x, oil immersion.

Figure 10 : Remnant of magnetite (dark grey) which is replaced by pyrite (white). This example represents a pyritized homogenous magnetite grain (black sand). The time and place of pyritization of this black sand constituent, as is the case with most other pyrite pseudomorphs, is unknown, but could well have taken place in the basin of sedimentation. Magnification 350x, oil immersion.

Figure 11 : Large abraded pyrite pseudomorph after a rhythmically banded iron-silica rich rock — most likely a type of banded ironstone. Magnification 50x, dry.

Figure 12 : Pseudomorph of pyrite and rutile after a hematite grain containing exsolution discs of ilmenite. The hematite portion has been replaced by pyrite (white), while the ilmenite fraction is now rutile (grey). The shape of the pseudomorph is a result of abrasion during transportation by water action. Part of an authigenic compact pyrite cube can be seen in the upper right hand corner of the photomicrograph. Magnification 350x, oil immersion.

PLATE 4

Figure 13 : Detrital rutile grain (dark grey and distinctly pleochroic) replaced peripherally by pyrite (white). This assemblage represents the initial stage of the formation of pyrite pseudomorphs after black sand constituents. Magnification 350x, oil immersion.

Figure 14 : Pyrite pseudomorph after rounded titaniferous magnetite. The magnetite portion is completely pyritized (white), whereas the exsolution lamellae of ilmenite are converted into rutile (dark grey). The ilmenite exsolution in the titaniferous magnetite parallel to (111) is perfectly preserved in the pseudomorph. Magnification 350x, oil immersion.

Figure 15 : A large, elongated concretionary pyrite nodule, shattered into three parts. A small grain of rounded compact pyrite has been moved into the space between the parts of the shattered nodule. Such shattered pyrite concretions occur only rarely in the Basal Reef. Small irregular aggregates of secondary reconstituted pyrite occur in addition to the smaller rounded detrital pyrite grains.
Magnification 50x, dry.

Figure 16 : Compact rounded pyrite grains (partly cataclastic) and a large, round, pyrite concretion. Because of the delicate structure of the concretion its rounded outline seems to be a concretionary phenomenon rather than an indication of prolonged transport. It appears that most of the concretionary pyrite was transported over only a short distance and was formed more or less in situ.
Magnification 50x, dry.

PLATE 5

Figure 17 : Typical large pyrite concretion together with much smaller detrital pyrite grains and a small pyrite concretion in the lower right hand corner of the photomicrograph.
Magnification 50x, dry.

Figure 18 : Same section as Figure 17, but etched with concentrated HNO_3 for 60 seconds. Both pyrite concretions are strongly attacked by the etching agent, whereas the detrital pyrite is only weakly affected. Note the distinct granular shaped structure which develops in the concretion after etching.
Magnification 50x, dry.

Figure 19 : Fractured pyrite concretion together with cataclastic compact rounded pyrite grains and small individuals of secondary remobilized pyrite. Chromite (grey) occurs as an extremely minor component.
Magnification 50x, dry.

Figure 20 : Part of a loosely knit pyrite concretion showing typical octahedral axial crosses. This skeleton growth developed from a single nucleus, by addition of further material. The very delicate structure is probably the result of fast growth or the non-availability of sufficient material during the growth. This concretion has undoubtedly formed in situ.
Magnification 350x, oil immersion.

PLATE 6

Figure 21 : A compact concretionary pyrite nodule in which the octahedral crosses are not visible.
Magnification 350x, oil immersion.

Figure 22 : The same section as Figure 21, but etched with concentrated HNO_3 for 30 seconds. The etching clearly reveals the axial crosses which gradually filled out during the growth of the concretion. This concretionary nodule apparently grew slower, or it had more material available than in the loosely knit concretion shown in Figure 20. Etching with HNO_3 is, therefore, extremely useful for recognizing pyrite concretions in the reef.
Magnification 350x, oil immersion.

Figure 23 : A porous pyrite nodule showing two intimately intergrown varieties of pyrite. The dark type is anisotropic and slightly softer than the more reflecting type. According to Saager and Mihálik (1967), these difference must be attributed to different As, Co, and Ni contents of the two pyrites. Such a pyrite aggregate probably formed from iron-rich silica gel by the addition of H_2S.
Magnification 350x, oil immersion.

Figure 24 : Spherical to subspherical structures of the "mineralized bacteria" type in a large pyrite nodule. This type of microstructure commonly occurs in cluster-like colonies and resembles some of the probable life forms described from the Elsburg A3 Reef by Schidlowski (1963 and 1965). The structures are also similar to "mineralized bacteria" reported from some German sulfide ore deposits.
Magnification 350x, oil immersion.

PLATE 7

Figure 25 : "Mineralized bacteria" structures in a large, porous, pyrite nodule. The spherical microstructures are randomly distributed throughout the entire nodule, their diameters measuring from 6 to 20 microns. The microstructures usually consist of two or three concentric layers apparently formed by quartz. Some of the concentric layers show distinct octagonal shapes, while others are almost perfectly round.
Magnification 350x, oil immersion.

Figure 26 : Same section as Figure 25, but with higher magnification. The octagonal shape of the microstructures is clearly observable. Where three layers occur it appears that the outer, as well as the inner layers are thicker and better developed than the middle layer.
Magnification 1000x, oil immersion.

Figure 27 : Pyrite aggregates consisting entirely of different shaped microspherical structures. Some of the spheres possess a relatively thick outer layer of pyrite. The cores are usually filled with quartz. It is interesting to note that along the edge of the pyrite nodule some of the globules are distinctly abraded. This suggests some transportation of the pyrite nodule.
Magnification 350x, oil immersion.

Figure 28 : Same section as Figure 27, but with a higher magnification. The outer layers of pyrite and the quartz cores of the "mineralized bacteria" are clearly visible. These microstructures show a weak tendency towards forming octagonal outlines in a similar manner to those in Figures 25 and 26.
Magnification 1000x, oil immersion.

PLATE 8

Figure 29 : "Mineralized bacteria" in a large porous pyrite nodule. These spherical structures occur in distinct colonies and measure between 3 and 10 microns. The cores of the structures are filled with quartz and show a distinct "dusting" by minute pyrite crystals.
Magnification 350x, oil immersion.

Figure 30 : Same section as Figure 29, but with higher magnification. The quartz cores of the microstructures and the fine pyrite "dusting" is clearly visible. The octagonal outlines of the "mineralized bacteria" as seen in Figures 25 and 27 are absent. These microstructures resemble somewhat the fromboidal forms described by Love (1957).
Magnification 1000x, oil immersion.

Figure 31 : Microspherical structures in a large pyrite nodule. These "mineralized bacteria" are very similar to those described in Figure 24. The large microsphere in the upper left hand corner of the photograph, however, resembles the form illustrated in Figure 27.
Magnification 350x, oil immersion.

Figure 32 : High magnification of the large microsphere of Figure 31. This structure is almost identical to that described by Schidlowski (1963 and 1965). He believes that the outer ring which envelops a central core-body is suggestive of the presence of an external sac.
Magnification 1000x, oil immersion.

PLATE 9

Figure 33 : Microspherical structures in a pyrite nodule. A peculiar feature of these forms are their pronounced egg-shaped, or elliptical outlines, especially in the middle part of the photomicrograph.
Magnification 350x, oil immersion.

Figure 34 : Same section as in Figure 33, but with higher magnification. The elliptical form of the microstructures is clearly visible.
Magnification 1000x, oil immersion.

Figure 35 : Microspherical structures in a pyrite nodule.
Magnification 350x, oil immersion.

Figure 36 : Microspherical structures in a elongated pyrite nodule. All the "mineralized bacteria" shown in Plate 9 have very similar forms. They possess a spherical layer of quartz around a pyrite core, which in some instances shows a "dusting" by minute gangue inclusions. The diameter of these structures measure between 5 and 15 microns. Ramdohr (1958) reported almost identical microstructures from the Black Reef, which is much higher in the stratigraphical column. The type of "mineralized bacteria" illustrated in Plate 9 has been found most abundantly in the Basal Reef. It is followed by the type showing two or three concentric layers and often a marked tendency to octagonal outlines (see Figures 25 and 26).
Magnification 350x, oil immersion.

PLATE 10

Figure 37 : Microstructures in a rounded porous pyrite grain. Two distinct layers are developed, appearing as stippled lines. The pyrite cores usually have a dusted appearance due to a fine interspersing with quartz. In a few cases the cores are completely replaced by gangue material. The outlines of most of these structures are distinctly pentagonal.
Magnification 350x, oil immersion.

Figure 38 : Circular forms in a rounded pyrite nodule. These structures, as well as the pentagonal forms of Figure 37 appear to represent rhythmic colloidal structures rather than probable life forms.
Magnification 350x, oil immersion.

Figure 39 : Idiomorphic authigenic pyrite crystal (white) in juxtaposition with a detrital uraninite grain (dark grey), containing minute grains of radiogenic galena (greyish white). Between the uraninite and pyrite is a seam of pyrrhotite (light grey). The alpha radiation of the uraninite caused destruction of the pyrite lattice and resulted in the formation of radial expansion cracks (left hand side of the photomicrograph). The pyrrhotite seam is believed to have formed from pyrite caused by radiogenic sulfur-substitution.
Magnification 350x, oil immersion.

Figure 40 : Pyrite cubes (white) in a matrix of galena (grey) which replaces the pyrite crystals. Gangue (black). This specimen is from a dyke contact and both minerals are of hydrothermal origin.
Magnification 350x, oil immersion.

PLATE 11

Figure 41 : Idiomorphic pyrite crystal (white) replaced by stromeyerite (dark grey and slightly light-etched) and by galena (grey and somewhat harder than stromeyerite). This section is from the same locality as the section shown in Figure 40. All minerals are hydrothermally emplaced and are related to the intrusion of a dyke.
Magnification 350x, oil immersion.

Figure 42 : Authigenic association of marcasite, pyrite (both white), pyrrhotite (grey) and mackinawite (dark grey). The formation of mackinawite (tetragonal (Ni, Co, $Fe_{1+x}S$) resulting from metamorphism, establishes a minimum limit to 135°C for the temperature reached during the metamorphism of the Witwatersrand sediments (Clark, 1966).
Magnification 350x, oil immersion.

Figure 43 : Intergrowth of authigenic pyrite and marcasite. Both minerals have been formed very late.
Magnification 350x, oil immersion.

Figure 44 : Same section as that seen in Figure 43, but with nicols incompletely crossed. The anisotropic marcasite in the centre of the intergrowth is clearly visible. Both minerals are of pseudohydrothermal origin.
Magnification 350x, oil immersion.

PLATE 12

Figure 45 : Shattered zircon grain (dark grey) healed by authigenic pyrite (white). No replacement has taken place and no radio-active blasting of the surrounding pyrite can be observed.
Magnification 350x, oil immersion.

Figure 46 : Zircon grain (dark grey) surrounded by authigenic pyrite (white). In this case, a very weak peripheral replacement and corrosion of the zircon by pyrite can be observed.
Magnification 350x, oil immersion.

Figure 47 : Compact pyrite idioblast grading outwards into porous idiomorphic pyrite. The distinct zonal arrangement of the numerous pores in crystallographic directions is clearly visible. This transition from compact into porous pyrite may be due to a faster growth of the marginal zone, possibly at lower temperatures (Ramdohr, 1958).
Magnification 350x, oil immersion.

Figure 48 : Compact pyrite idioblast overgrown by loose porous pyrite. In principle, Figure 48 shows the same phenomenon as Figure 47, but with no zonal arrangement of the pores. The formation of the porous idiomorphic pyrite must have taken place at a very late stage, because no remobilized base metal sulfides or gold migrated into the pores. The porous overgrowth is identical to the pyrite encrustations illustrated in Figure 7.
Magnification 350x, oil immersion.

PLATE 13

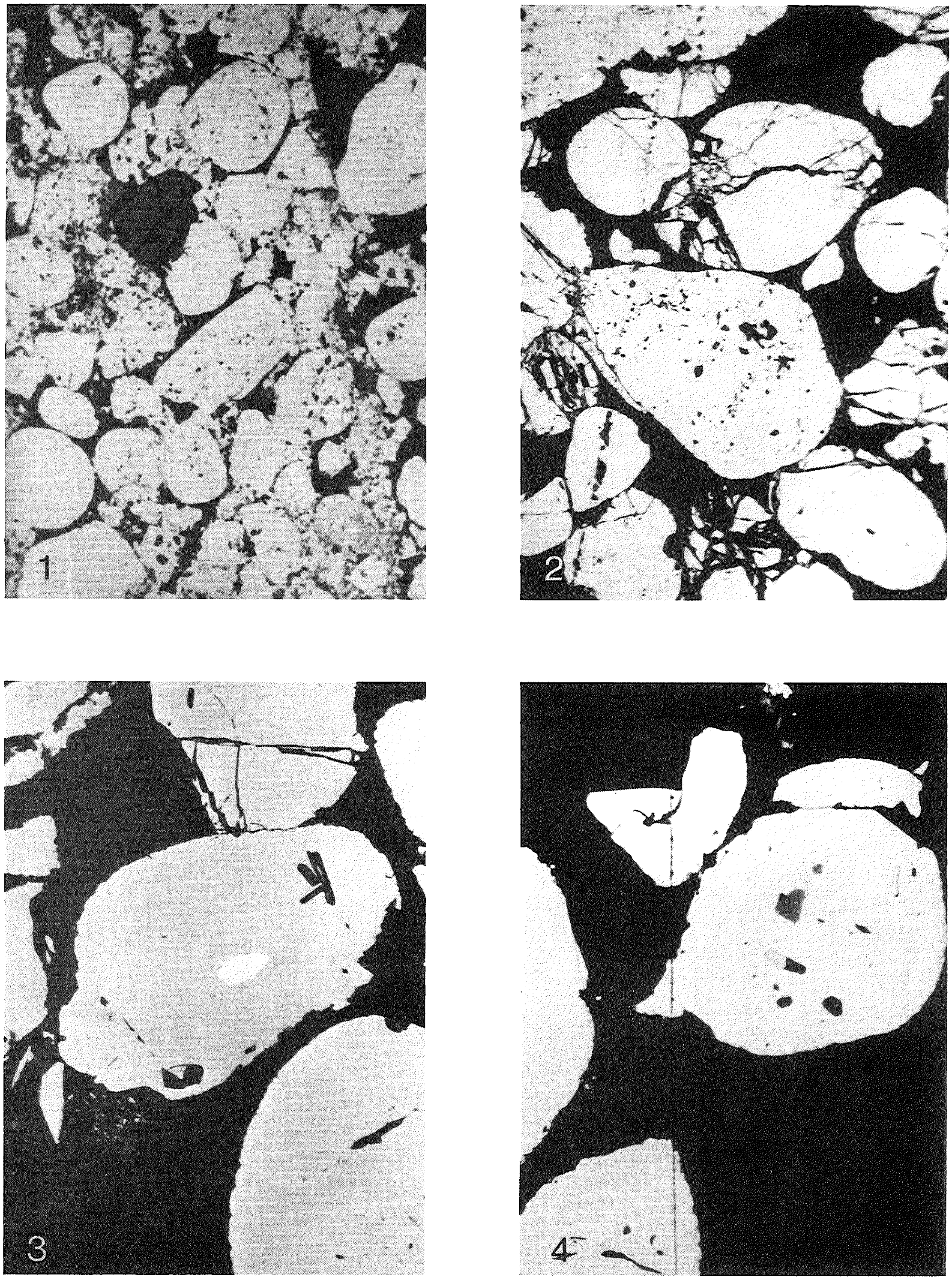
Figure 49 : Part of a large porous authigenic pyrite grain. The distinct zonal arrangement of the numerous pores in crystallographic directions is apparent. This differs from the randomly distributed pores which occur in the porous concretions and in the porous rounded pyrite. See Figures 15 and 16.
Magnification 350x, oil immersion.

Figure 50 : Rounded pyrite with pores arranged crystallographically. In spite of the fragile structure this pyrite appears to have been transported and abraded. The aggregate is possibly an authigenic pyrite grain which formed part of an older ore-horizon which was eroded, reworked and redeposited. The more compact marginal zone apparently saved the fragile core from complete destruction during transport.
Magnification 350x, oil immersion.

Figure 51 : Vein-pyrite healing fractures in an allogenic detrital chromite grain (grey). The vein-pyrite has been mobilized during the metamorphic stage and is thus pseudohydrothermally emplaced. A replacement of the chromite by the pyrite does not take place. The higher reflecting marginal rim of the chromite is caused by a higher iron and lower aluminium and magnesium content of these zones.
Magnification 350x, oil immersion.

* *

PLATE 1



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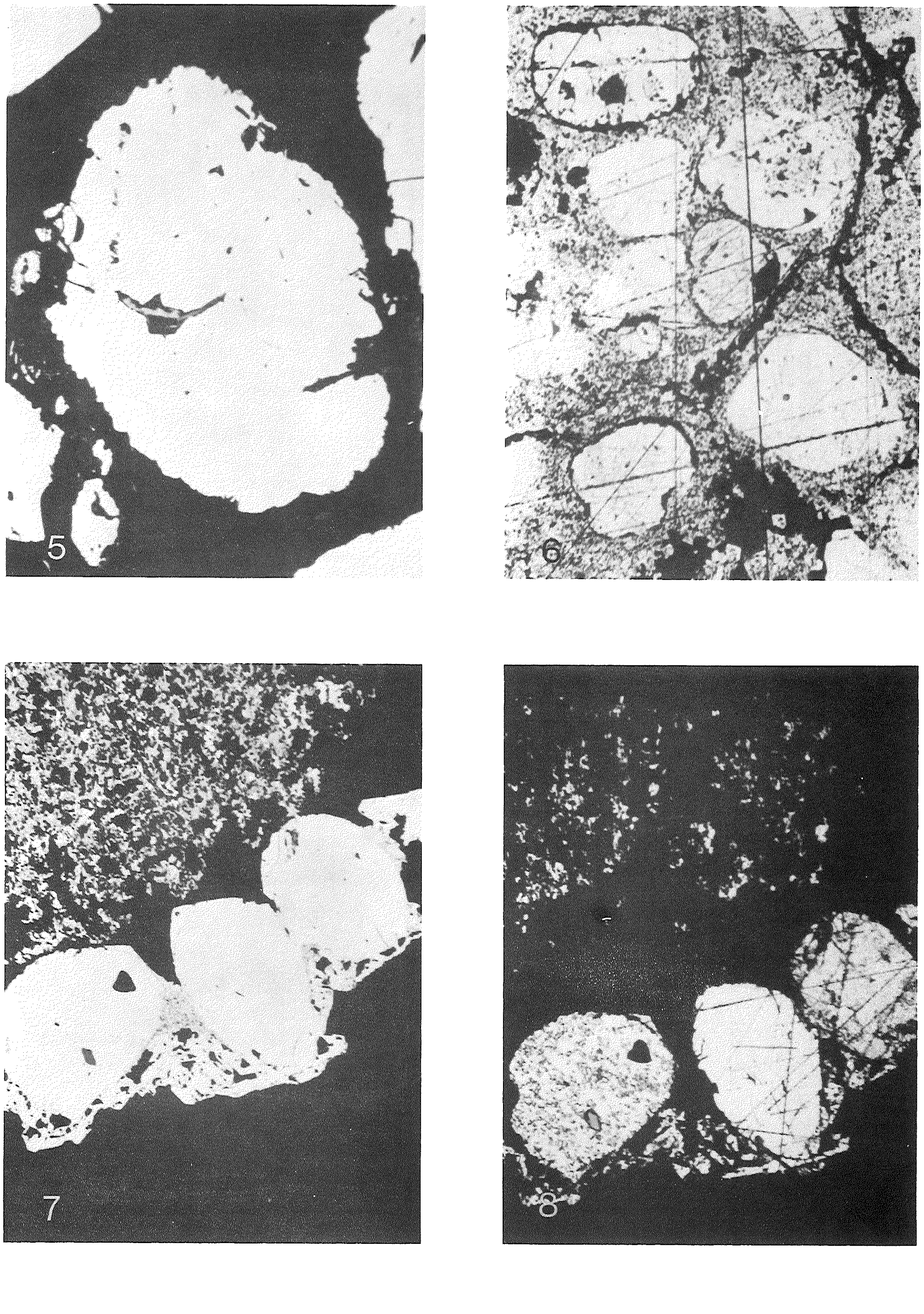

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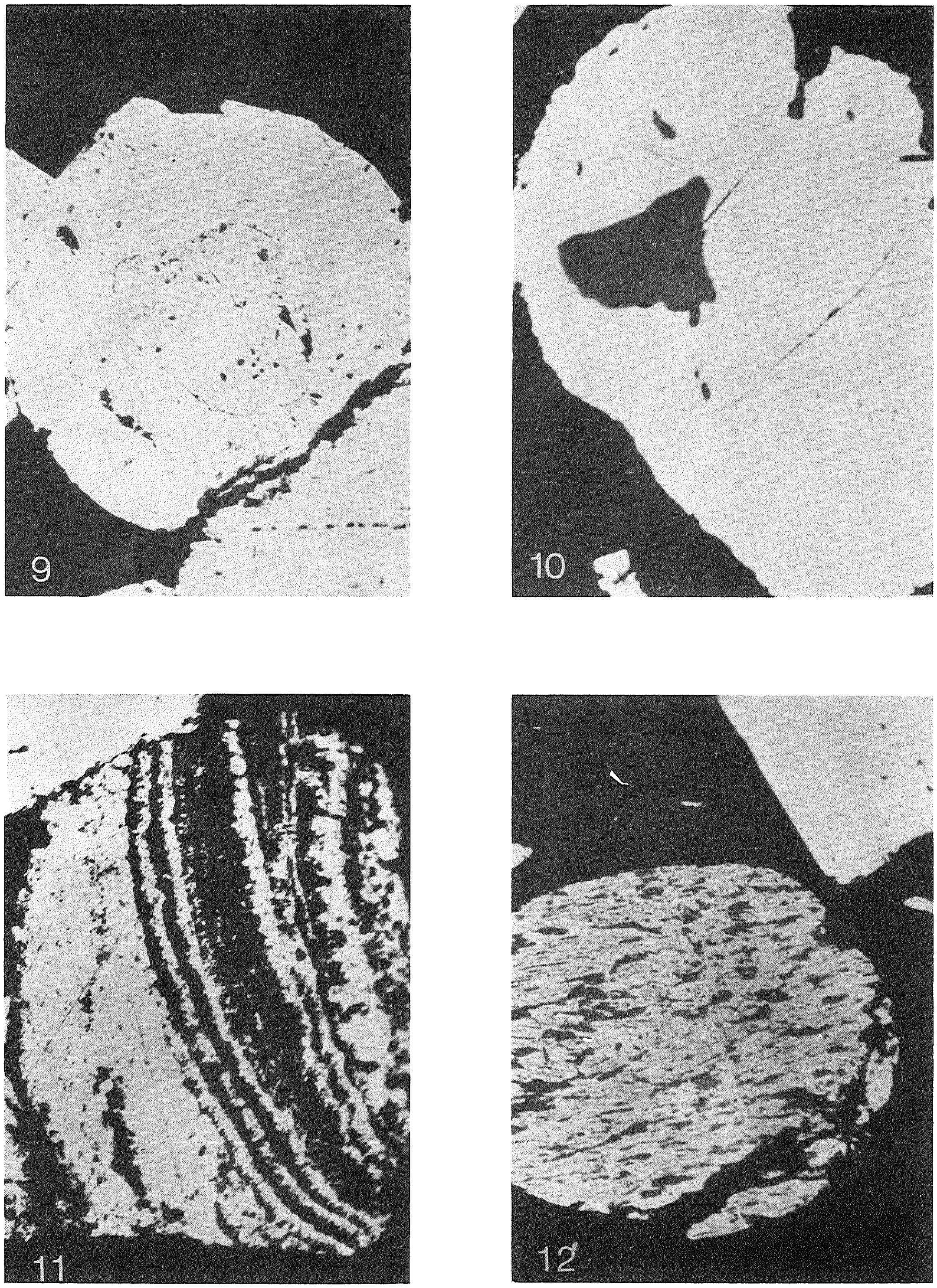

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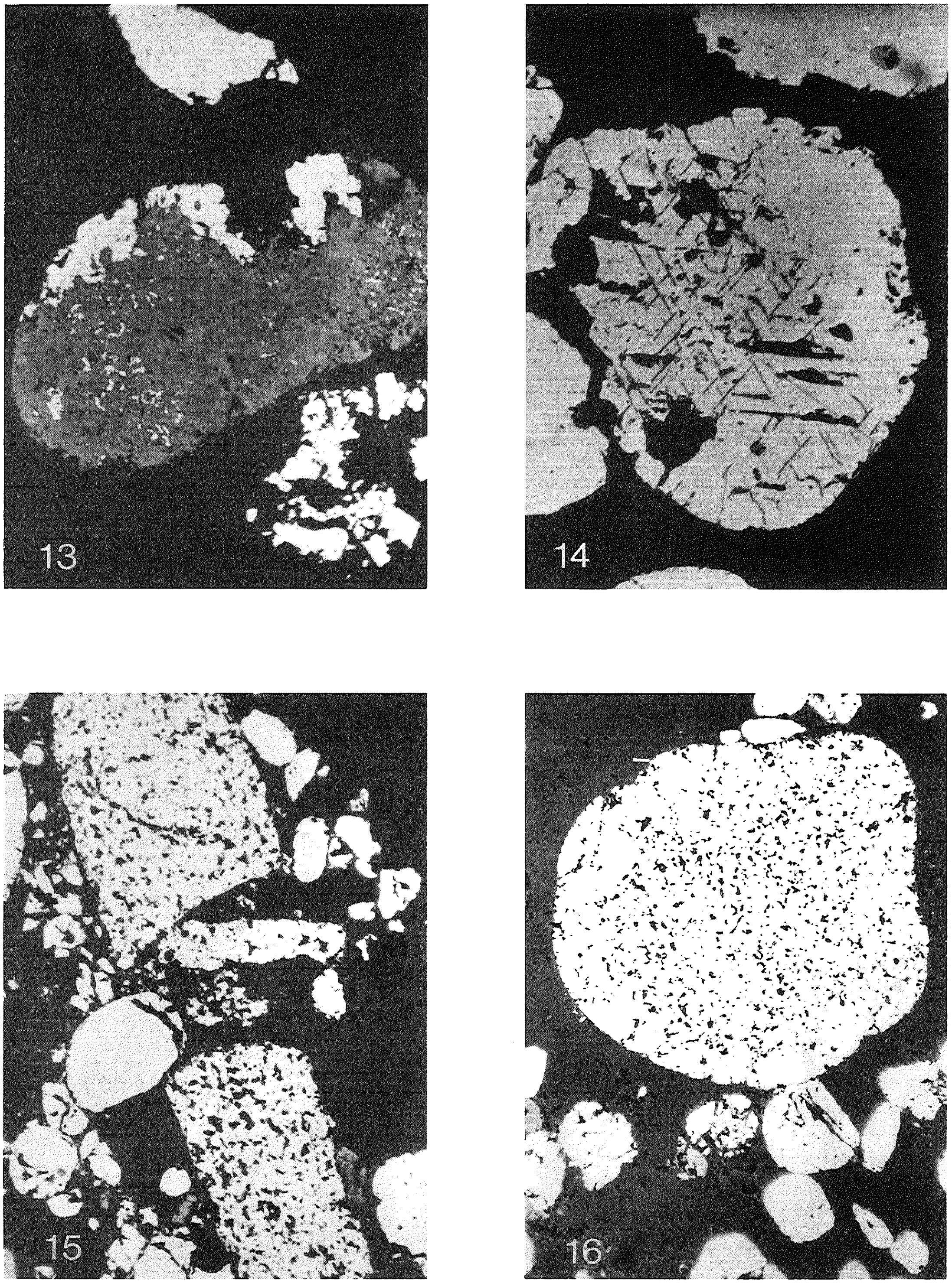

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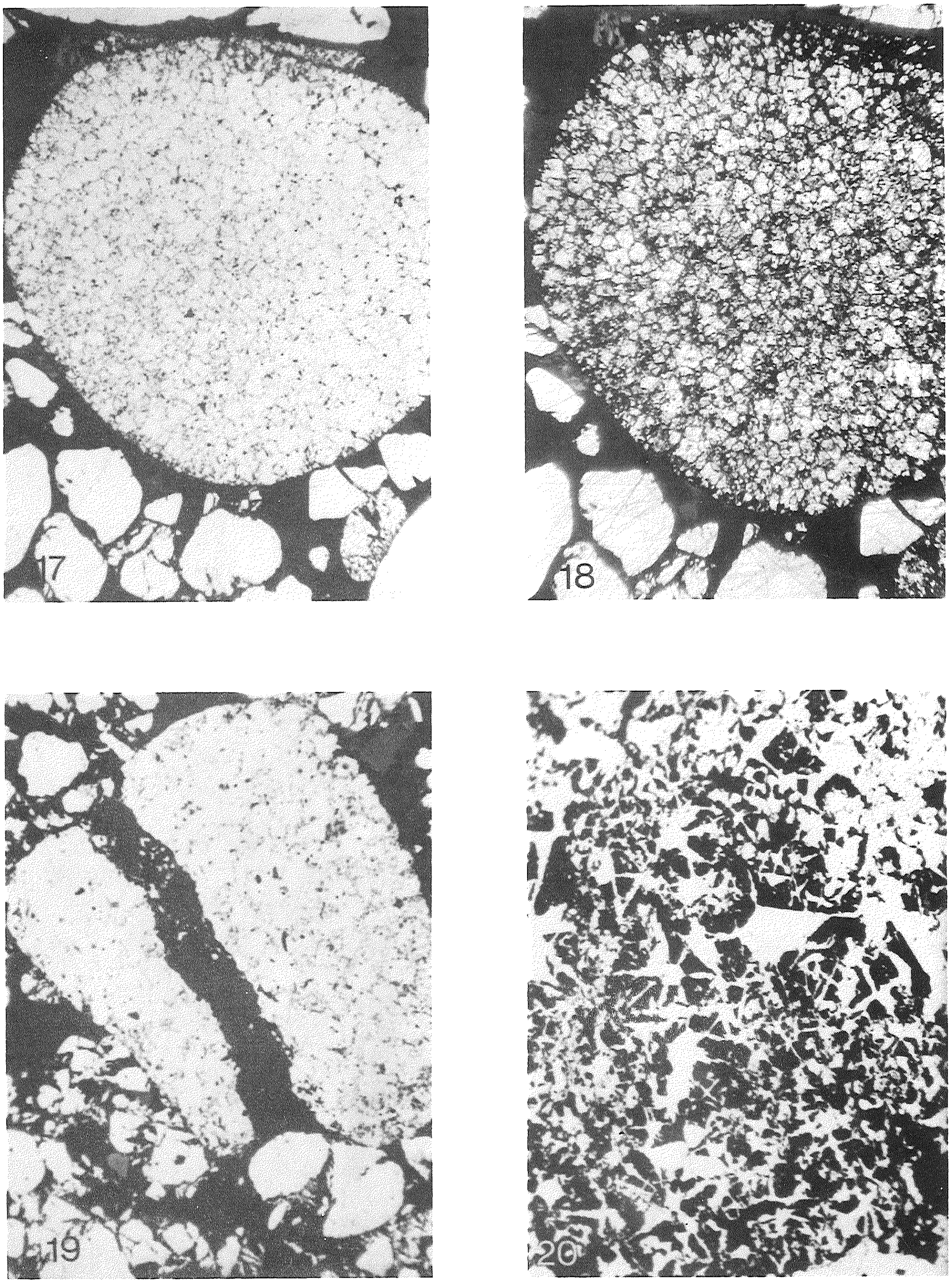

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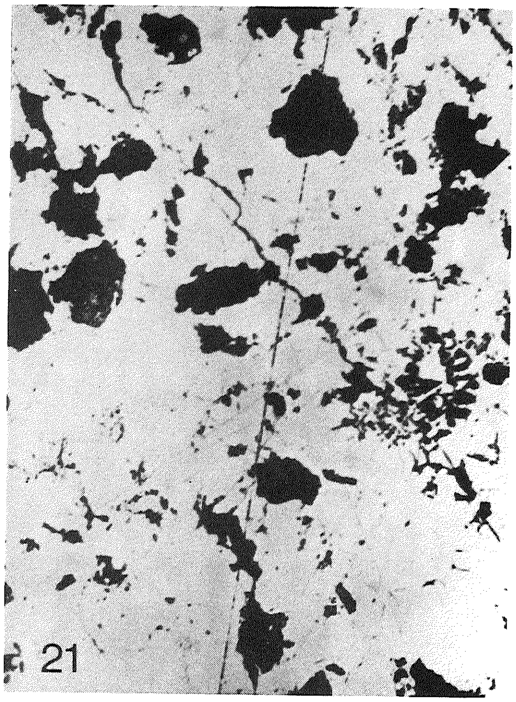

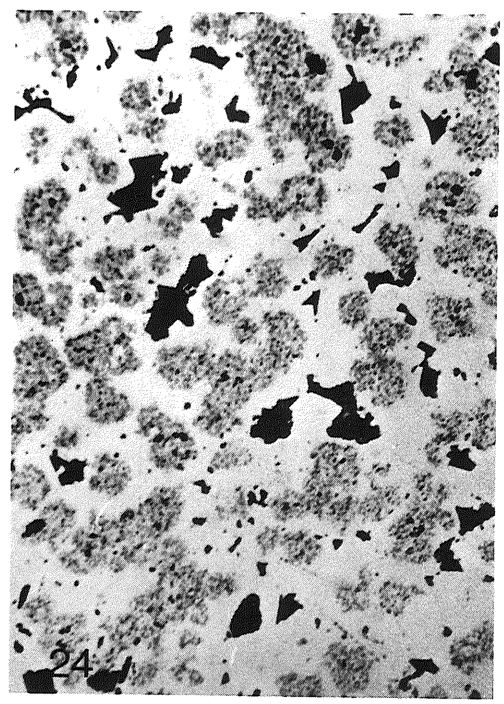

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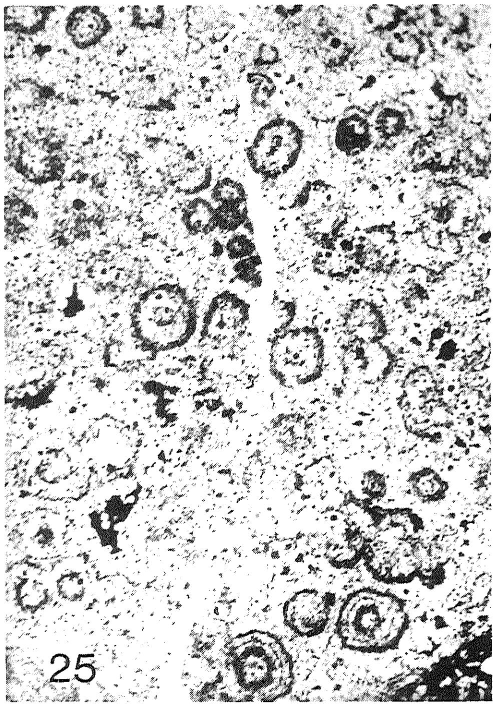

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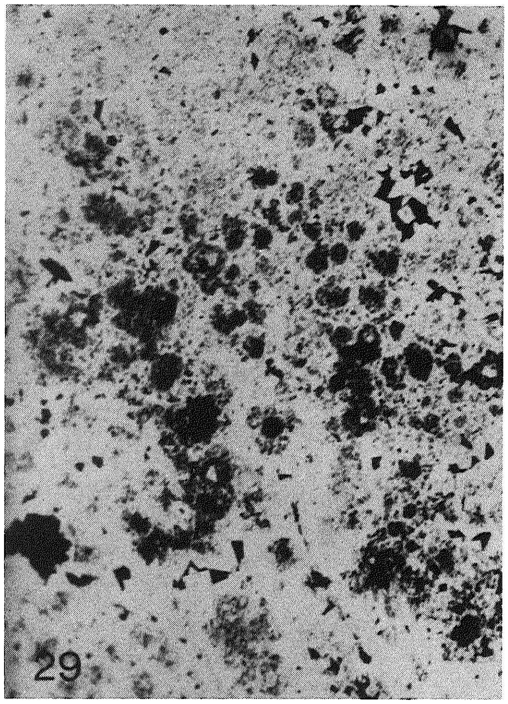

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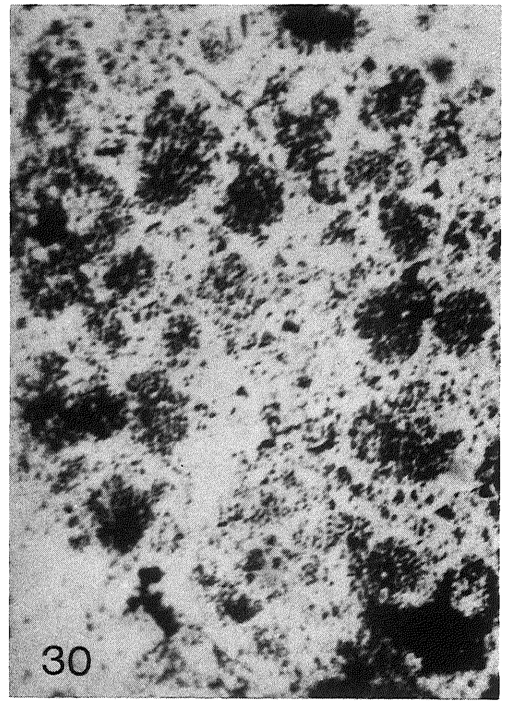

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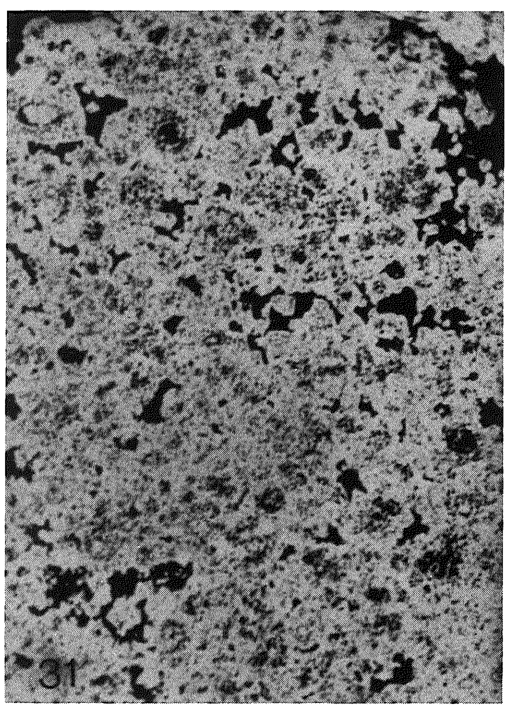

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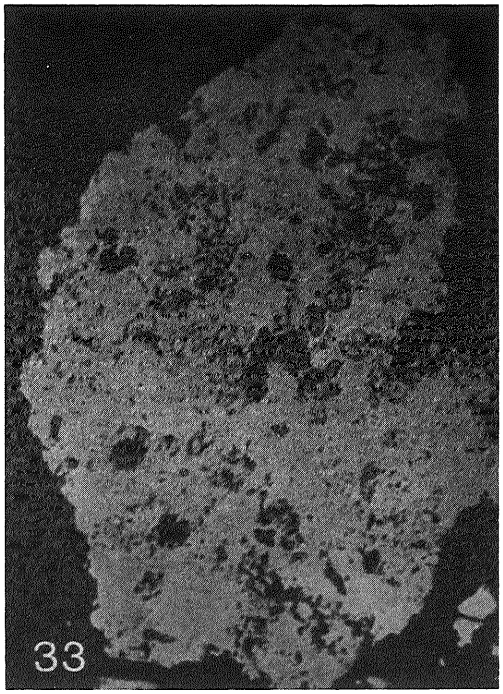
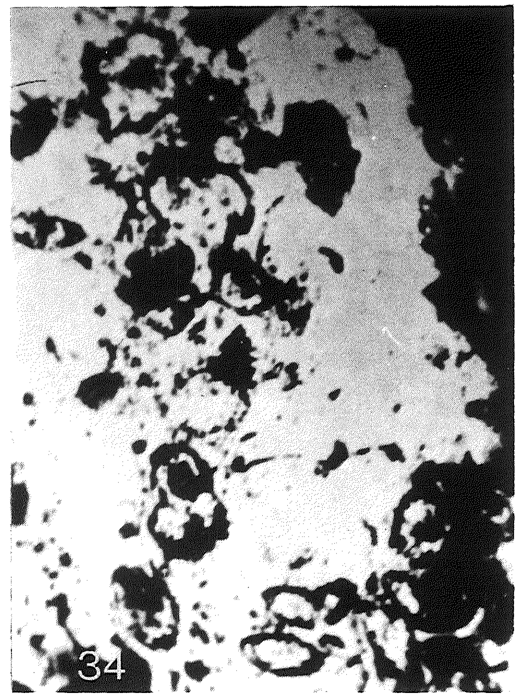
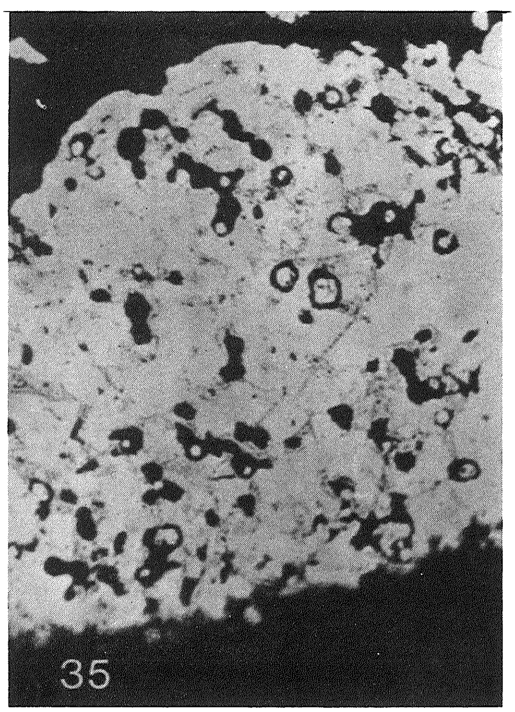
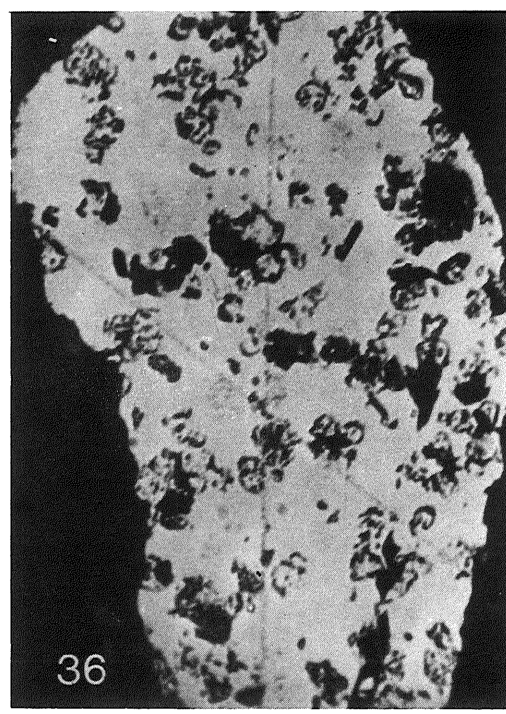
PLATE 9









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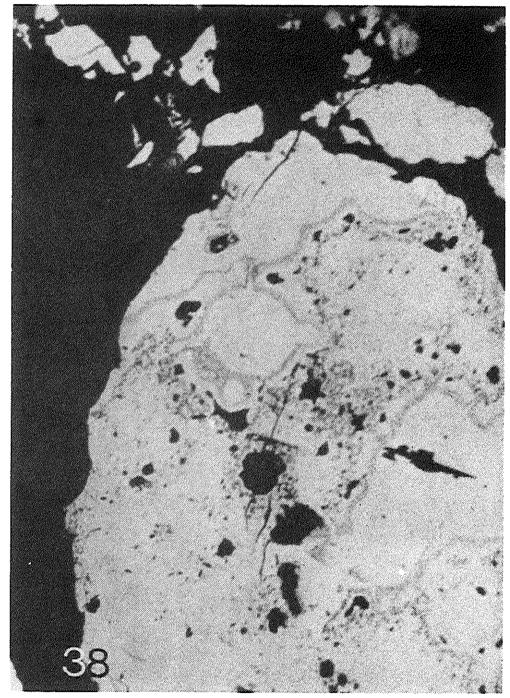

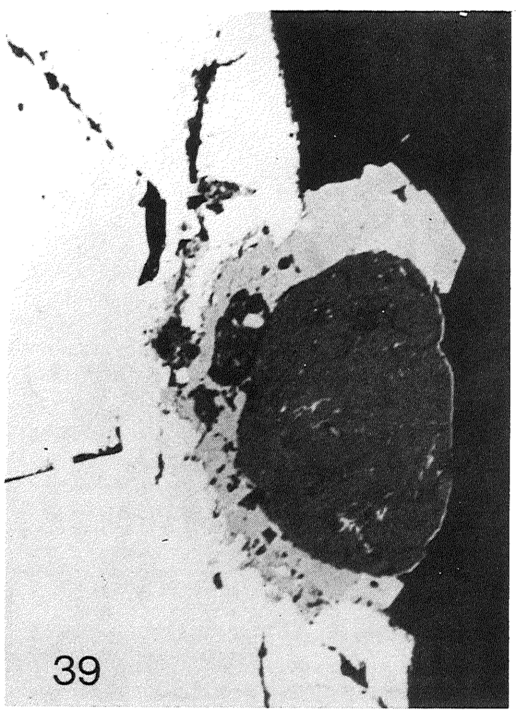

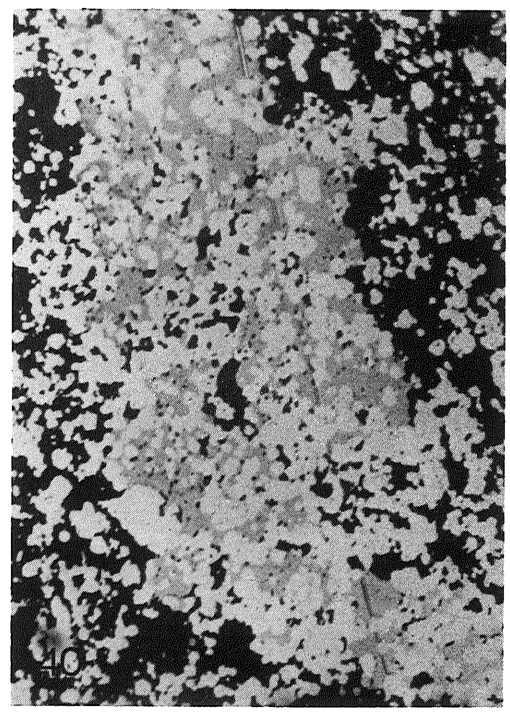

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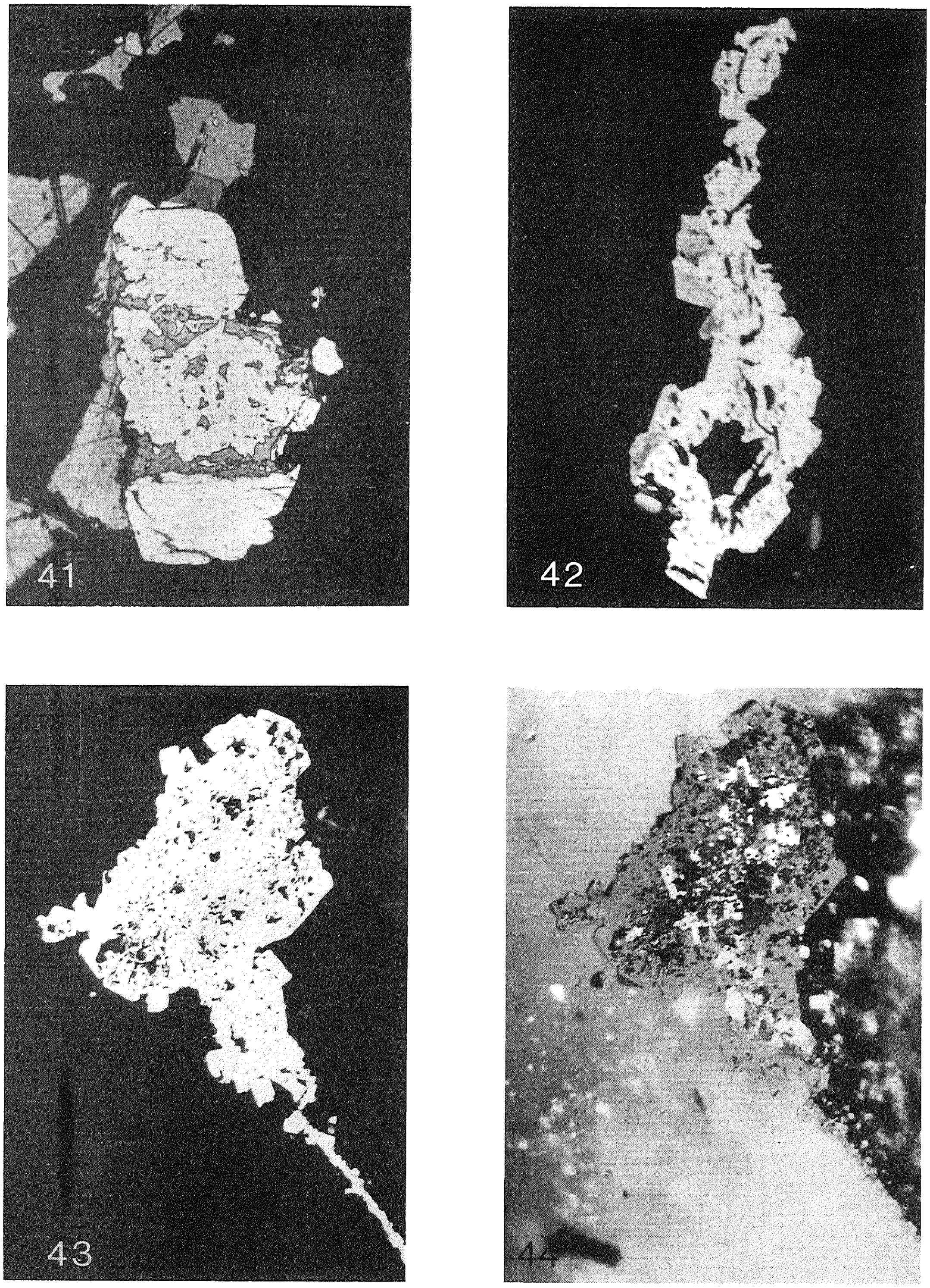

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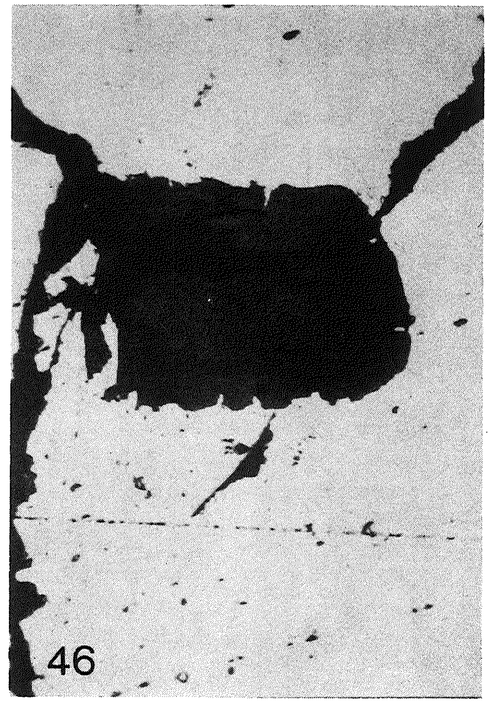

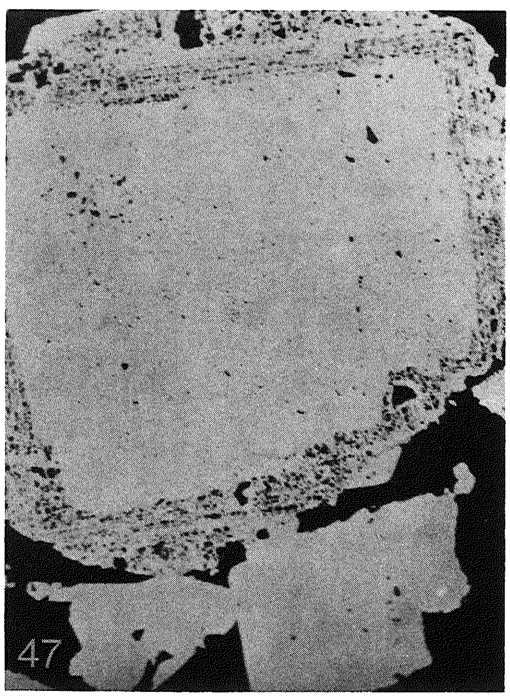

PLATE 13