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Significance of Diagenesis for the Origin of Witwatersrand-Type Uraniferous Conglomerates [and Discussion]

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Significance of diagenesis for the origin of Witwatersrand-type uraniferous conglomerates

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[Plate 1]

A petrographic study of pyrite may be the key to the understanding of the Witwatersrand (South Africa) gold–uranium deposits: the sediments of the Witwatersrand Supergroup contain at least nine types of pyrite, namely (1) Laminated pyrite seams; (2) pyrite nodules in shales; (3) pyrite nodules in quartzite and conglomerate; (4) pyrite as overgrowths on carbonaceous filaments; (5) pyrite filling pore spaces and replacing clasts; (6) pyrite replacing detrital magnetite; (7) allogenic fragments of laminated pyrite; (8) allogenic fragments of pyrite nodules; and (9) allogenic fragments of coarse-grained pyrite. Types 1–6 probably formed during diagenesis of the sediment due to the activity of sulphate-reducing bacteria; types 7 and 8 are transported fragments of diagentic pyrite; type 9 may be of diverse origin, but may also in part be transported fragments of diagenetic pyrite.

Pyrite petrography suggests a multi-stage history of ore enrichment: diagenetic precipitation of gold, uraninite and pyrite in sediments containing organic matter, followed by erosion, transport of allogenic fragments of ore minerals for short distances, and concentration in lag gravels at channel bottoms and unconformities. Repeated cycles of weathering, diagenetic precipitation from weathering solutions, erosion, minor transport and redeposition may have caused the extraordinary enrichment of the ores on major unconformities in the Upper Witwatersrand Supergroup.

Introduction

It is the purpose of this paper to point out that uraniferous conglomerates of the Witwatersrand Supergroup, studied during underground visits to mines in the Witwatersrand district, contain an important ore component of diagenetic origin. Some ore minerals have been formed *in situ* during the diagenesis of the ore-bearing strata. Others, consisting of allogenic fragments of diagenetic ore minerals are probably intraclasts derived from older Witwatersrand rocks. An additional component may be derived from an Archaean terrain and/or from volcanic rocks intercalated with the Dominion Reef and Witwatersrand sediments.

The origin of the Witwatersrand ore bodies can be deduced from a petrographic study of pyrite, which takes many forms; some are formed *in situ*, as the result of diagenetic sulphate reduction, and some are transported allogenic fragments. Many of the allogenic pyrite fragments in the Witwatersrand conglomerates can be interpreted as intraclasts derived from pyrite precipitated in older Witwatersrand sediments. A substantial part of the uranium and gold contained in the Witwatersrand conglomerates is directly associated with diagenetic pyrite precipitated *in situ* and with allogenic fragments of diagenetic pyrite.

The association of detrital and diagenetic pyrite in sandstones and conglomerate is unusual, but has been reported from other Precambrian and Phanerozoic sequences, for example by Rocheleau (in Dimroth *et al.* 1975) from the Archaean and by Hubert (1973) from the Cambrian. Detrital pyrite occurs in many fluvial placers (Ramdohr 1966, p. 741), in eskers and fluvioglacial gravels of Quebec (P. LaSalle, personal communication 1974) and in alluvium of the Moselle Valley in Germany (Müller & Negendank 1974). Detrital pyrite will in general be oxidized but can be preserved if reducing diagenetic conditions are established rapidly after deposition. Diagenetic pyrite is also likely to occur under these conditions.

Detrital grains of thorian uraninite, together with authigenic and allogenic pyrite, are known from Holocene sands of the upper Indus River (Simpson & Bowles 1977). Thus, detrital concentrations of pyrite and uraninite occur under atmospheric conditions at present and survive diagenesis in a favourable tectonic and sedimentary environment. There is no reason to assume therefore that deposition of detrital pyrite and uraninite in the Witwatersrand conglomerates occurred under an oxygen-deficient atmosphere (Schidlowski 1971; Cloud 1972; Pretorius 1976). On the contrary, diagenetic precipitation of uranium, gold and pyrite in association with organic matter most probably indicates the presence of oxidizing atmospheric conditions for the transport of uranyl and sulphate ions in solution (Simpson & Bowles 1977). Saager (1970) recognized in-situ pyrite formed by sulphate reduction and Kimberley (1974) proposed that the mineralization of the Witwatersrand conglomerates has been precipitated during diagenesis. Dimroth & Kimberley (1976) and Dimroth & Lichtblau (1978) concluded that the Early Precambrian atmosphere was enriched in oxygen from studies of the distribution of carbon, sulphur, uranium and iron in sedimentary rocks, from oxidation of Archaean palagonite and the presence of ferric oxide crusts on Archaean pillow basalts.

Petrography of pyrite in the Witwatersrand Supergroup

In-situ pyrite

Sedimentary rocks of the Witwatersrand Supergroup contains at least six types of pyrite formed *in situ*, namely (1) laminated pyrite seams; (2) pyrite nodules in shales and siltstones; (3) pyrite nodules in quartzites and conglomerates; (4) pyrite overgrowths on the replacement of carbonaceous filaments; (5) pyrite overgrowths on allogenic pyrite, filling pore spaces and marginally replacing of chert and quartz clasts; and (6) replacement of iron ores by pyrite.

(1) *Laminated pyrite seams*

Laminated pyrite seams occur up to a few centimetres in thickness, for example, above the 1/a reef in the Cooke section of the Randfontein Estates G.M.C. (R. F. Tucker, guide). The

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Description of plate 1

Figure 1. Pyrite nodule in Kimberley Shale: 8-level crosscut, Bracken Mine, Evander. Sample no. S.A.1-3.

Figure 2. Allogenic pyrite is concentrated in the lower part of foresets. The laminae of allogenic pyrite can be followed across the nodule to the left. Cooke Section, Randfontein Estates G.M.C. Sample no. S.A. 5–1.

Figure 3. Fibrous carbon seam from Carbon Leader reef, Blyvooruitzicht G.M.C. Pyrite is interstitial to carbonaceous filaments. Sample no. S.A. 6–1.

Figure 4. Allogenic fragment of finely crystalline pyrite with parallel lamination. Such pyrite is clearly diagenetic. Cooke Section, Randfontein Estates G.M.C. Sample no. S.A. 5–2.

Figure 5. Pyrite with radial and concentric texture characteristic of diagenetic marcasite nodules. This pyrite aggregate might have formed *in situ*, during the diagnesis of the sediment. Gd reef, Cooke Section, Randfontein Estates G.M.C. Sample no. S.A. 5–2.

Figure 6. Broken and abraded allogenic fragment of pyrite with radial and concentric texture. The fragment is probably an intraclast derived from a marcasite nodule formed in earlier Witwatersrand sediments. Gd reef, Cooke Section, Randfontein Estates G.M.C. Sample no. S.A. 5–2.

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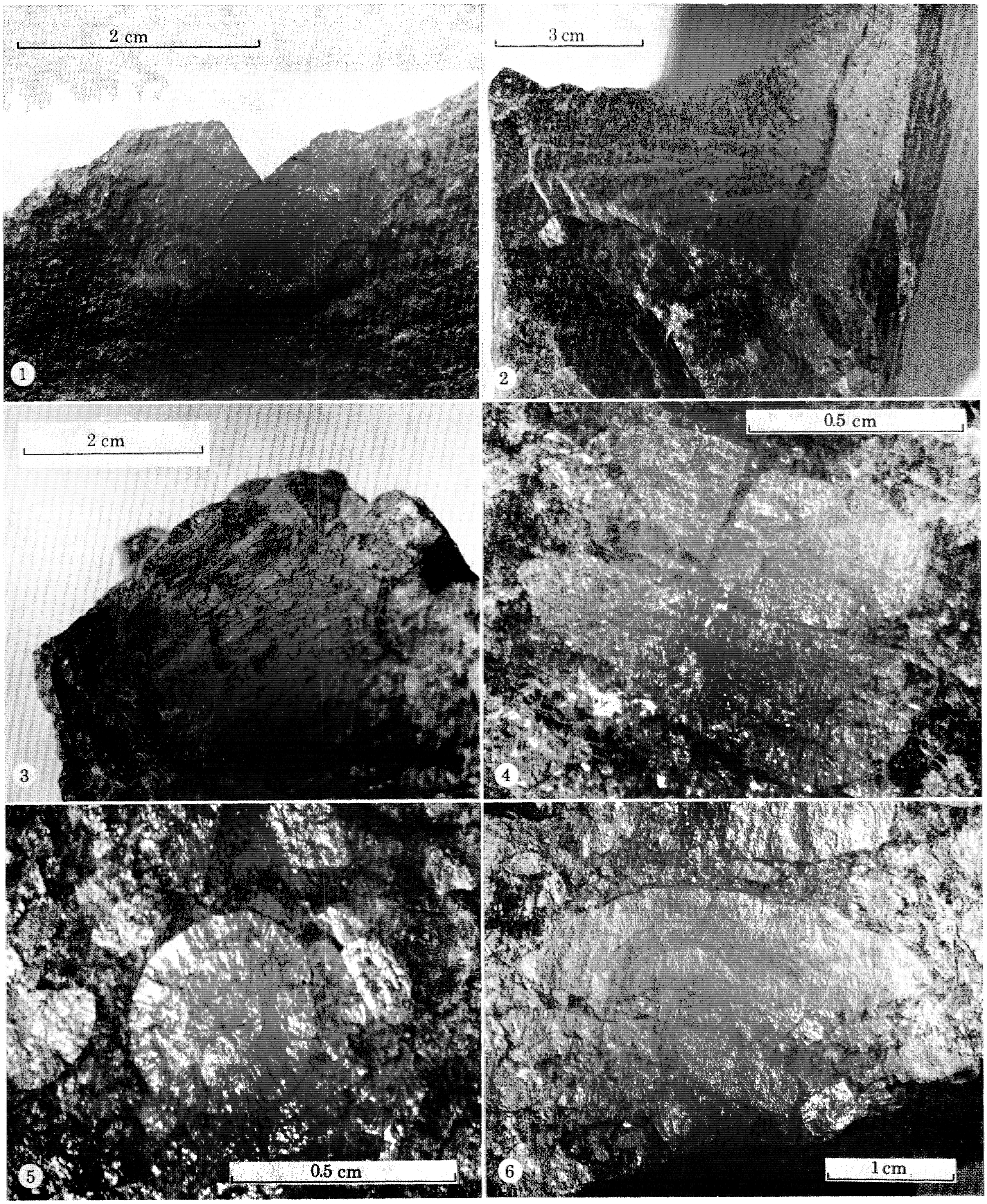

FIGURES 1–6. For description see opposite.

pyrite grades into clay seams. It is fine-grained with parallel lamination defined by variable grain size of crystallites and admixture of clay and organic matter.

(2) *Pyrite nodules in shales*

Pyrite nodules are present in the Kimberley Shale at the 8-level crosscut, Bracken Mines Ltd, Evander. Nodules are several centimetres in diameter, and are composed of fine-grained pyrite. They are generally concentrically laminated, with variable grain size and admixture of clay minerals. Radial texture, defined by crystal elongation is less common. The nodules are embedded in a moderately bituminous shale. Figure 1, plate 1, shows a specimen of Kimberley shale containing a pyrite nodule.

(3) *Pyrite nodules in quartzite and conglomerate*

Pyrite nodules in quartzite and conglomerate have been observed at two localities, namely in the quartzite separating the l/a and Gd reefs of the Cooke section of Randfontein Estates G.M.C., and in drillcore from the Evander gold field shown at Bracken Mines Ltd (R. F. Tucker was my guide at the Cooke Section).

Nodules at the Cooke section (figures 3 and 4) are several centimetres to several decimetres in diameter, and are sub-spherical to ellipsoidal in outline. They are set in a weakly bituminous quartzite. A concentric growth pattern is defined by variation of the size of pyrite crystallites and by an increase of the proportion of pyrite from the core to the margin of the nodules. The detrital texture of the quartzite is very well preserved in the centre of the nodule, where pyrite is interstitial to quartz and chert grains. It is less well preserved at the margin, where small remnants of the original clasts are overgrown by pyrite. Nodules observed at Evander are about 1 cm in diameter and show concentric laminations with variable crystal size and radial texture emphasized by crystal elongation, and resemble marcasite nodules in Phanerozoic sedimentary rocks.

(4) *Pyrite overgrowths on carbonaceous filaments*

Filamentous carbonaceous seams occur below, above and within reefs in parts of the Witwatersrand Supergroup and grade laterally and vertically into clay seams in the Blyvooruitzicht G.M.C. (Dr D. K. Hallbauer, guide). The carbonaceous fibres are approximately perpendicular to bedding, and are overgrown and partly replaced by gold and uranium-rich minerals (Hallbauer & Van Warmelo 1974). Pyrite columns are interstitial to carbonaceous filaments (figure 3).

(5) *Pyrite as pore space-filling and replacement*

Medium to coarsely crystalline pyrite commonly overgrows allogenic pyrite (Utter 1977, fig. 9.6) and is locally continuous with aggregates of medium to coarsely crystalline pyrite which fill the inter-particle pores in quartzites. Marginal replacement of quartz and chert clasts by medium to coarsely crystalline pyrite is commonly observed. Replacement proceeded from the margin toward the centre of the clasts and pyrite aggregates replacing clasts are physically continuous with pyrite filling pore spaces. Also, medium, coarsely and very coarsely crystalline (crystal diameter up to 10 mm) pyrite porphyroblasts replace the rock, cutting across the sedimentary fabric. These varieties of pyrite are identical to the 'authigenic idiomorphic to hypidiomorphic pyrite and pyrite accumulations' of Utter (1977).

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(6) *Replacement of detrital magnetite by pyrite*

Ramdohr (1960, p. 738) indicates that some pyrite in Witerwatersrand conglomerates was formed by replacement of iron oxides, and Schidlowski (1966) documented pyrite grains of this type which is uncommon (D. K. Hallbauer, personal communication 1977; W. E. L. Minter, personal communication 1977).

Allogenic pyrite

Three types of allogenic pyrite are readily distinguished in hand specimen, namely (7) fine to medium grain size pyrite with parallel laminations, (8) fine to medium grain size pyrite with radial and concentric texture and (9) coarse to medium grain size pyrite aggregates and rounded or edge-rounded single crystals of pyrite. All three types have been well documented by previous authors, particularly by Saager (1970) and Utter (1977). Types 7 and 8 correspond to the 'allogenic rounded porous pyrites' and type 9 to the 'allogenic rounded compact pyrites' of Utter (1977).

(7) *Fine to medium grain size pyrite with parallel lamination*

Fragments of dark, fine to medium grain size pyrite are common in the ore-bearing conglomerates (figure 4) and have been well documented by Utter (1977). Fragments are of sand to gravel size. Sand-sized fragments are subspherical, large fragments are discoidal. Some very flat discoidal fragments, up to several centimetres long and about 5 mm thick, have been observed. Fragments are well rounded and show a parallel lamination defined by variations of crystal size and variable admixture of bituminous shale. Utter (1977) documented inclusions of heavy minerals in this type of pyrite, in particular of zircon. Sand-sized fragments very commonly show effects of compaction: they bear spherical indentations at opposite poles and a system of radial racks perpendicular to the indentations (Utter 1977, figs, 8.5, 8.6 and 8.7).

(8) *Fine to medium grain size pyrite with radial and concentric texture*

Pyrite fragments with radial and concentric texture (figures 5 and 6) also are common, and have been documented by Schweigart & Von Rahden (1965) and by Utter (1977). Schweigart & Von Rahden interpreted these grains as ooids; Utter named them 'colloform pyrites'. The fragments are of sand or pebble size and generally are subspherical. The surfaces of many fragments are subparallel to the concentric lamination and such grains may have formed *in situ* (figure 5). In other fragments, concentric laminations have been truncated, and a few broken pieces of such pyrite have been observed (figure 6). Concentric textures generally are defined by variable grain size and admixture of clay minerals and bitumen; radial textures are defined by elongation of crystals. Some fragments show botryoidal, warty concentric laminations (Utter 1977, fig. 9.9).

(9) *Medium and coarse grained abraded pyrite aggregates and abraded pyrite crystal*

Fragments of medium to coarse grained pyrite are bright yellow in hand specimen. They are of sand to pebble size. Larger fragments commonly are discoidal. Some fragments show weak lamination. Rounding is poor to excellent. Rounded or edge-rounded pyrite crystals and pyrite aggregates are an important component in sandstone and in pebbly sandstones of the ore bearing reefs in the Witwatersrand Supergroup. They commonly show traces of the idiomorphic crystal faces. Scanning electron micrographs by Utter (1977, figs 6–7*b*, 6–9*b*) show surficial etch pits. This type of pyrite has been named 'allogenic rounded compact pyrite' by Utter (1977).

Origin of pyrite

Much of the in-situ pyrite of the Witwatersrand Supergroup petrographically resembles pyrite which, in Holocene sediments, can be observed to form by diagenetic sulphate reduction. Many of the allogenic pyrite fragments resemble diagenetic pyrite and have shapes which preclude transportation over large distances; such pyrite fragments are probably intraclasts derived from older Witwatersrand rocks. Much, perhaps most, of the pyrite in the Witwatersrand Supergroup could ultimately be of diagenetic origin.

In-situ pyrite

Laminated pyrite of the Witwatersrand Supergroup (type 1) resembles laminae of iron sulphide forming in Holocene sediments by preferential replacement of organic-rich laminae (Berner 1970, 1971). Pyrite nodules in shales (type 2) are like nodules in Phanerozoic shales; occasionally they have radial and concentric textures indicating their derivation from marcasite nodules. Pyrite interstitial to organic filaments in bituminous seams (type 4) formed during diagenetic pore space-filling; this type of pyrite is analogous to replacement and overgrowth of fossils by pyrite in Phanerozoic sedimentary rocks. In all three cases, pyrite is associated with organic matter which suggests an origin by sulphate reduction.

Pyrite nodules in quartzite (type 3) and much of the medium to coarse grained pyrite aggregates (large part of type 5) form a pore space-filling between clasts and marginally replace these clasts. Such pyrite must have formed during the early diagenetic cementation of the quartzite and is analogous to pyrite cements as they are found in Phanerozoic sandstones. On the other hand, coarsely crystalline pyrite aggregates, filling fractures across clasts and pyrite porphyroblasts independent of the sedimentary fabric (part of type 5), evidently grew after the cementation of inter-particle porosity. Such pyrite formed during or after late diagenesis. The age and origin of pyrite as replacement of iron oxides (type 6) is more likely to occur at an early diagenetic stage but a late diagenetic or metamorphic age cannot be excluded.

Allogenic pyrite

The fine grained allogenic pyrite fragments (types 7 and 8) are similar to laminated and nodular pyrite in the Witwatersrand Supergroup and in many other sedimentary sequences. They are undoubtedly fragments of diagenetic pyrite. Aggregates of such fine grained pyrite are subject to abrasion during transport and the large size and discoidal shapes of many fragments of types 7 and 8 pyrite preclude transport over large distances. These fragments are probably intraclasts derived from pyrite formed *in situ* in older Witwatersrand sediments. Utter (1977) and Minter suggest (personal communication 1977) that these pyrite fragments have been generated in a fluvial or lacustrine setting and also interpret them as intraclasts.

The source and origin of the fragments of coarse grained pyrite (type 9) is problematical. There is no petrographic criterion for distinguishing between this type of pyrite derived from volcanic, metamorphic or unmetamorphosed sedimentary rocks. Some may be diagenetic since pyrite filling pore spaces (type 5) in the Witwatersrand is coarse grained. Furthermore, pyrite porphyroblasts in shales and graywackes commonly show pressure shadows; thus, much coarse-grained pyrite formed in sedimentary rocks before deformation and regional

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metamorphism is probably diagenetic. Some type 9 pyrite fragments are flat discoidal and/or show vague parallel lamination. Such fragments are probably derived from sedimentary rocks.

It is probable that some of the coarsely crystalline pyrite is derived from Witwatersrand and Dominion Reef strata: the Witwatersrand contains medium to coarsely crystalline diagenetic pyrite (type 5) and both contain volcanic rocks, normally a rich source of pyrite. Some of this pyrite could have been redeposited, since sediments of the Lower Witwatersrand and of the Dominion Reef are the immediate source of the Upper Witwatersrand strata.

Genetic model

The petrography of pyrite and relations between carbonaceous matter, pyrite, gold and uraninite in the Witwatersrand Supergroup suggests a complex history of ore enrichment. First, the ore bodies contain an allogenic component that may be derived from an Archaean source area (Pretorius 1976) and/or from volcanic rocks of the Dominion Reef Group and the Witwatersrand Supergroup. The thorian uraninite and some of the coarsely crystalline allogenic pyrite may belong to this component. Secondly, a substantial part of allogenic pyrite, in particular the finely crystalline allogenic pyrite fragments (types 8 and 9), are probably intraclasts derived from older Witwatersrand sediments; these allogenic pyrites of ultimately diagenetic origin are rich in gold (Utter 1977). Both generations of ore minerals were concentrated as placers at the bottom of braided-stream channels (Pretorius 1976). The placers were further enriched in gold and uranium during their diagenesis. The gold and pitchblende in the pyrite layers (type 1 pyrite) and in carbon seams are part of this third generation of ore minerals, as are, possibly, the gold overgrowths on type 5 pyrite and the gold included in the coarsely crystalline allogenic pyrite (type 9). Finally, there was some remobilization of the ore minerals during subsequent metamorphism (Pretorius 1976).

In summary, it is proposed that a substantial part of the Witwatersrand mineralization may ultimately be of diagenetic origin. Part of the allogenic ore minerals may have been precipitated from weathering solutions in sediment containing organic matter. During uplift of older Witwatersrand strata at the basin margin, they would be eroded, transported for a short distance, and concentrated in placers at the bottom of fluvial channels. They would survive diagenesis if rapidly buried below the water table together with organic matter, so that reducing diagenetic conditions were rapidly established after deposition. Ores would be further enriched during diagenesis of the sediment when oxidized weathering solutions drained into the reducing ore beds. Repetition of these processes during successive tectonic cycles may be the cause for the unusual enrichment of the ore-bearing strata in the upper part of the Witwatersrand Supergroup.

Ore bodies of this complex origin can form only in a specific tectonic and sedimentary environment, such as the environment for the Witwatersrand basin described by Pretorius (1975, 1976): the margin of the sedimentary basin is uplifted in successive cycles so that overlap of younger over older strata occurs and components of younger strata are derived from older strata. Transport at each stage is for a short distance and sedimentation rates are high. The sedimentary environment was richly vegetated as indicated by seams of carbonaceous filaments (remnants of algal mats; Hallbauer & Von Warmelo 1974) and by the abundance of finely distributed organic matter in the ore bearing strata.

Concentration of ore minerals occurred on foresets and channel bottoms, and also in carbonaceous seams. The presence of allogenic and diagenetic ore minerals is also important, with significant concentrations at the base and at the top of upward fining fluvial cycles.

Supporting sedimentological evidence

Many sedimentological features of the uraniferous conglomerates are difficult to reconcile with the classical placer hypothesis, but are consistent with the hypothesis proposed here. In particular, (1) terrigenous detritus shows mineralogical and textural maturity, gold and pyrite are immature; (2) heavy mineral concentrations are not commensurate with concentrations of gold, uraninite and pyrite; (3) pyrite, gold and uraninite are closely associated with reducing diagenetic environments and with conglomerates filling channels.

Maturity of sediments

The terrigenenous detritus of the Witwatersrand Supergroup shows high textural and mineralogical maturity. Sediments are subarkoses composed mainly of quartz and chert fragments. Detrital feldspar is subordinate and granitic fragments are absent; the few lithic fragments are of porphyry and volcanic rocks which are probably derived from the lower Witwatersrand Supergroup. Terrigenous components are well rounded. Comparison with Recent sands and gravels suggests that terrigenous components of the Witwatersrand Supergroup were transported for at least several hundred kilometres, and underwent strong chemical weathering.

The ore minerals, by contrast, are immature. Detrital gold grains still show traces of the original crystal shape, only slightly deformed at their edges during transport (Hallbauer 1977). The intensely hammered sheets produced during long fluvial transport are absent. Consequently, it has been proposed that gold has been transported for distances not exceeding 5–30 km (Hallbauer 1977).

Much of the pyrite also shows immature grain shapes: many flat discoidal slabs of porous, fine-grained, laminated pyrite are present; such slabs are very fragile and cannot survive transport for substantial distances. Allogenic pyrite nodules commonly show little surficial abrasion; some are broken, abrasion has rounded corners but the original concentric lamination is still largely parallel to the grain surface. Thus, allogenic pyrite nodules also have been transported for not more than a few kilometres. Consequently, it is assumed that the terrigenous detritus and the ore minerals are not derived from the same source area. Archaean rocks situated several hundred kilometres from the basin are the ultimate source of most of the terrigenous detritus, whereas gold and pyrite have been transported only for a much shorter distance. It must be assumed therefore, that the ultimate source of much of the allogenic pyrite and gold was within the Witwatersrand basin.

Absence of heavy minerals

Normally, heavy minerals are a major constituent of gold placers which commonly contain 30% or more of detrital magnetite and commensurate quantities of zircon, monazite, etc. The ore-bearing conglomerates of the Witwatersrand Supergroup, on the other hand, contain no substantial concentration of heavy minerals, and contain no detrital magnetite whatsoever.

Concentrates of pyrite from the B-reef of Loraine G.M.C. Co., kindly provided by Dr D. K. Hallbauer, contain a few grains of zircon as the only heavy mineral component.

It has been claimed (Pretorius 1976; Minter 1975) that the separation of gold, uraninite and pyrite from heavy minerals is due to hydrodynamic selection. Grains of zircon hydrodynamically equivalent to the gold and uraninite grains are rare in the Archaean source rocks. However, the source rocks commonly contain large grains of magnetite and this mineral, at least, should be enriched with the ore minerals. No such enrichment is found. Furthermore, modern gold placers do contain substantial amounts of heavy minerals, although their source rocks do not greatly differ from the source of the Witwatersrand sediments. Of course, absence of heavy mineral concentration, and particularly of magnetite, from the Witwatersrand ores is to be expected if the allogenic ore minerals are intraclasts derived from earlier Witwatersrand rocks.

Association with reducing diagenetic conditions

From inspection of the Witwatersrand ore deposits, I have concluded that allogenic ore minerals survived only where reducing diagenetic conditions were established rapidly after deposition. Nearly all ore-bearing conglomerates contain some carbonaceous matter, which survives diagenesis only under reducing conditions. Furthermore, some of the seams richest in gold and uranium do not occur in the conglomerates, but occur in carbonaceous shales and in carbonaceous seams associated with the conglomerates.

Reducing diagenetic conditions in Early Precambrian sediments have conventionally been related to the existence of an oxygen-free primordial atmosphere. The fact that Early Precambrian palagonite has been oxidized and that some Early Precambrian pillow basalts bear ferric oxide crusts (Dimroth & Lichtblau 1978), and sedimentological evidence (Dimroth & Kimberley 1976) preclude this hypothesis. The Witwatersrand ore deposits contain evidence for deposition under an oxygen-rich atmosphere: diagenetic precipitation of uranium by carbonaceous matter in this locality seems to require oxidizing atmospheric conditions to maintain the uranyl and sulphate ions in solution during transport to their site of deposition (Simpson and Bowles 1977); etch-pits in allogenic pyrite grains (Utter 1977, figs 6–7*b*, 6–9*b*) can form only by oxidation. Thus, reducing diagenetic conditions in the ore-bearing conglomerates of the Witwatersrand Supergroup must have been produced by decay of organic matter co-sedimented with the terrigenous detritus.

I am deeply indebted to the Geological Society of South Africa for defraying my expenses during a one month visit to South Africa, and to Professor W. Van Biljon for his kind hospitality at Rands Afrikaans University. Dr W. E. L. Minter, Dr D. K. Hallbauer, Mr R. F. T. Tucker and the staff geologists of Bracken Mines Ltd and of West Driefontain G.M.C. kindly guided me during visits underground. Dr F. J. Pettijohn and Dr W. E. L. Minter commented a first draft of this paper and their constructive criticism is gratefully acknowledged. I thank Miss Janet Demarcke for the preparation of the photographs.

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Discussion

R. Saager (*Institute for Mineralogy and Petrology, University of Cologne, Zülpicherstr.* 49, *D-5 Köln, Germany*). Classification of Witwatersrand pyrite has been undertaken in detail by Ramdohr (1958) and Saager (1970). In a broad sense both these authors distinguish between (i) allogenic rounded compact pyrite, (ii) rounded porous, often concretionary pyrite, and (iii) authigenic idiomorphic to hypidiomorphic pyrite. The first type of pyrite is of detrital origin. Its source area is the hinterland of the Witwatersrand sediments. The second type formed within the basin of deposition possibly with the aid of sulphate-reducing, sulphide-producing bacteria. It generally was transported only over limited distances and formed before and/or during diagenesis. The rounded porous pyrites exhibit conspicuously large diameters and constitute the largest proportion of the so-called 'buckshot pyrite' which often are as large as a hazelnut. The third type of pyrite has formed by recrystallization during metamorphism of the Witwatersrand sediments.

Lead isotope investigations (Köppel & Saager 1974) on the porous pyrite variety reveal no unequivocal results. They indicate either a formation of these pyrites *in situ* before and/or during diagenesis or a late formation, 2040 Ma ago, during the metamorphism of the sediments.

The classification proposed in Professor Dimroth's paper is entirely based on macroscopic observations and comprises mainly pyrites belonging to the group of large porous pyrites, the so-called buckshots. Professor Dimroth's classification must therefore be regarded with care in order to avoid confusion with the microscopic classifications of the earlier mentioned authors. Therefore, it might be worthwhile to use a different nomenclature for the subdivision of the macroscopic pyrite structures.

In contrast to Professor Dimroth, most recent students of the Witwatersrand agree that the detrital compact pyrite variety generally forms the greatest percentage of all rounded pyrite grains, and only in certain areas of the deposit can rounded porous pyrite be observed as the most abundant pyrite type (Utter 1977). Diagenetic ore formation is certainly present in the Witwatersrand deposits, but it does not play the dominating rôle proposed by Professor Dimroth; for this reason it is not necessary to postulate an oxidizing atmosphere for the deposition of the Witwatersrand ores.

Investigations carried out on uranium-bearing and gold-bearing pyrite conglomerates in the Archaean of the Northern Transvaal (Saager & Muff 1977) reveal that the sedimentary concentration processes which ultimately led to the formation of the Witwatersrand deposits prevailed over a long time-span of more than 500 Ma, during which detrital uraninite and pyrite at least periodically were exposed to the atmosphere. Therefore, the occurrence of non-economic accumulations of detrital uraninite and pyrite in Holocene sands of the upper Indus River, as cited by Professor Dimroth, cannot in my opinion be used as an indication that the Witwatersrand uraninites and pyrites during their sedimentary transport were able to survive an oxygen-rich atmosphere, as the contact time of the Indus uraninites and pyrites with the present atmosphere was of comparatively very short duration.

References

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C. E. Feather (*Anglo American Research Laboratories, P.O. Box* 106, *Crown Mines, Tvl.* 2025, *Republic of South Africa*). Most experienced Witwatersrand geologists will agree that there is evidence that some of the pyrite is of secondary origin, notably the accumulations of idiomorphic and hypidiomorphic grains. However, it is generally agreed that this non-allogenic pyrite was formed after burial, during a period of metamorphic activity, rather than by diagenesis during burial. The bulk of the pyrite is undoubtedly of primary allogenic origin. Abundant evidence in favour of a placer origin has been presented over a long period, resulting from careful systematic studies by a large number of sedimentogists and mineralogists. As an example, in a recent study by scanning electron microscope, Utter (1977) has shown that the bulk of the pyrite grains are allogenic, and belong to two broad classes: (1) allogenic rounded compact pyrites, derived from source rocks in the hinterland of the Witwatersrand basin, and (2) allogenic rounded porous pyrites which were formed as mud-balls from detrital pyrite muds or iron sulphide gels (the only evidence for limited possible diagenesis) on the surface of the alluvial fans.

It is incorrect to state that commensurate quantities of heavy minerals do not accompany the gold, uraninite and pyrite. There are abundant pseudomorphs of leucoxene after detrital ilmenite and titanmagnetite grains; and cobaltite, arsenopyrite, chromite and zircon are common allogenic grains. Other detrital minerals present include molybdenite, platinum groups minerals, monazite, xenotime, apatite and even diamond. W. E. L. Minter (1977, personal communication) reports that, in the Orange Free State, the distal deposits contain as much as 2 % zircon.

The suggestion that gold has been transported for less than 30 km is a subject for debate. If Professor Dimroth cites Hallbauer's (1977) evidence based on grain shapes and surface features is cited, it should be noted that most investigators of the Witwatersrand believe that the gold has been extensively reworked during metamorphism, and original shapes and features are likely to have been destroyed.

Thus it is my belief that it is unnecessary to invoke an oxygenic atmosphere for deposition of the Witwatersrand ores.

References

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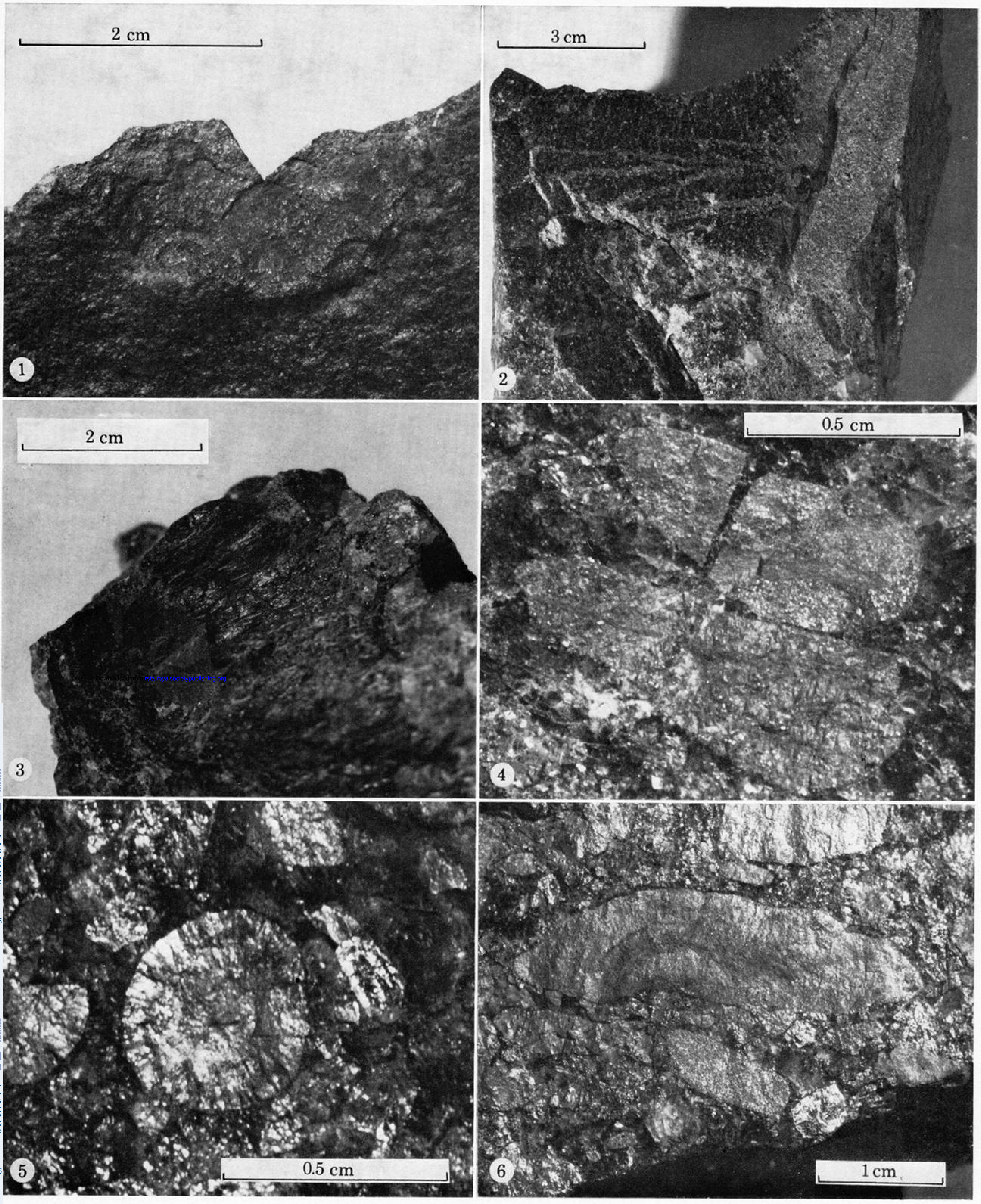
E. Dimroth. It is, perhaps, unfair to reply to a discussion with new data at hand: since the writing of my manuscript I have studied some 20 polished thin sections (size 5 cm × 7 cm or larger). Such large, polished thin sections are uniquely suited for sedimentological work because they permit the determination of the opaque and non-opaque minerals and therefore allow precise analysis of the sedimentary, tectonic and metamorphic fabric.

Microscopic work has confirmed that my classification of pyrite is objective and reproducible; types (5) and (9) can be subdivided. Over 50 % of allogenic pyrite fragments in my thin sections clearly show the petrographic characteristics of diagenetic pyrite. Much of the remainder may ultimately be of diagenetic origin but this cannot be demonstrated conclusively.

The distribution of allogenic pyrite and of over 80 % of the in-situ pyrite is determined by the sedimentary fabric; both kinds are cut by healed tectonic fractures. They cannot possibly have formed during a phase of metamorphism 2040 Ma ago, regardless of their lead isotope ratios. Less than 20 % of the in-situ pyrite fills tectonic fractures or occurs as porphyroblasts independent of the sedimentary fabric. That generation of pyrite, alone, can be regarded as metamorphic.

My thin sections contain less than 0.2 % of non-opaque heavy minerals (zircon, apatite, monazite, xenotime, etc.), an amount normal for sandstones and conglomerates. It would be premature to comment on the petrography of gold.

The geological time interval within which pyritic conglomerates formed in South Africa is irrelevant for pyrite stability: pyrite stability is determined (1) by the time-span that each grain was exposed to the atmosphere and (2) by the composition of interstitial fluids after burial of the pyrite grains. Fluvial transport is not a continuous process: grains are eroded from existing sediment, are moved rapidly, redeposited, and buried; they are exposed to the atmosphere only for brief intervals. Placers at channel-bottoms may form and be covered by sand during a single flood. Detrital pyrite will survive within the sediment if protected by products of organic decay. Some of my thin sections contain carbon, clear evidence that organic matter was present in the sediment and provided the conditions necessary for the survival of detrital pyrite and for the formation of in-situ pyrite during diagenesis.



FIGURES 1–6. For description see opposite.