ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
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BOTSWANELLA : A BACTERIA-PRODUCED CONCRETION FROM THE VENTERSDORP SEQUENCE OF BOTSWANA

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INFORMATION CIRCULAR No. 57

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by

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ABSTRACT

The *Botswanella* nodules have been found in the Mogobane shales which have been placed in the Ventersdorp Sequence, considered to be about 2300 million years old. The occurrences are located at the Mogobane Dam, Botswana, at 24°58' S., 25°42' E. The nodules are characterized by some consistent features of shape, size, and interior structure, which is composed of a system of concentric and radial elements. In several respects, the nodules resemble a concretion named *Telemarkites enigmaticus Dons 1959*, which has been described from the Late Precambrian Telemark Formation in Norway (age ca. 800-1000 million years). Most investigators of the *Telemarkites* problem have interpreted the nodules as concretions formed by algae; others have considered an origin in colonies of spongi or stromotoporae. Specimens of *Telemarkites* submitted by Dr. J. A. Dons enabled a direct comparison with *Botswanella* to be made. The following techniques were applied in the studies : thin-sections were examined under polarized light; polished-sections were analyzed under the ore microscope and the X-ray micro-analyzer; separate samples taken from different parts of the bodies were subjected to X-ray diffraction analyses; other samples were treated with macerating solutions.

The results show that *Botswanella* and *Telemarkites* must be regarded as generally different in nature and origin. *Telemarkites* has been found to contain considerably higher amounts of globe-shaped algal bodies, which appear to be arranged in colonies. The specimens resemble certain members of Cyanophyceae, which are known to drift in swab-like colonies in sea water. It is probable that the algae were silicified by gelatinous silica during their life time. The siliceous solutions are believed to have been derived from submarine volcanic eruptions, which took place in the vicinity of the depositional area. The algal remains are preserved three-dimensionally in the core of the nodules, which is composed of a mixture of fine-grained quartz and low-temperature albite. Apparently, the core became the centre of subsequent reactions which formed the exterior rims of the nodules. This mode of formation resembles, in some respects, that of the so-called "molar tooth" structures occurring in siliceous limestones of the Beltian System of North America. The "molar tooth" structures were found to have been formed by silicification of algal colonies. In contrast to the *Telemarkites* algae, however, these colonies were composed of filamentous types covering the sea bottom.

The *Botswanella* concretions do not contain any algal remains. However, sheet-like structures, resembling iron bacteria, have been detected. *Botswanella* structures were not contemporaneous with sedimentation, but are believed to have been formed by tectonic processes which took place between Ventersdorp and Waterberg times (ca. 2300-1500 million years). During this structural deformation, gravity sliding caused slip along the bedding planes of the Mogobane shales. In consequence of these processes, spaces which had been opened between the bedding planes were filled with precipitations of iron compounds brought in by groundwater solutions. The *Botswanella* concretions are considered to be alteration products of these iron precipitations, caused by the reaction between the reducing effect of organic matter present in the shales and the oxidizing activity of iron bacteria, which were also probably brought in by the groundwater. The *Botswanella* remains must be regarded as an example of post-depositional contamination.

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A. INTRODUCTION

The *Botswanella* nodules were first found by field geologists of the Geological Survey of Botswana. The structures occur in shaly sediments of the Mogobane Formation of the Ventersdorp Sequence. The size, shape, and structure of the nodules exhibit some features which were thought to indicate a possible biological origin. Against this tentative interpretation is the high age of the enveloping sediments, which are regarded to be ca. 2300 million years old. Organisms having the considerable dimensions of the nodules described could scarcely be expected at such an early time. According to Dons (1959), nodules of the same size and shape and of a similar interior structure have been found in Late Precambrian rocks in Norway. These structures, named *Telemarkites enigmaticus*, occur in the Telemark Formation, which is believed to be 800-1000 million years old. Other concretions known from the literature (Smith, 1948; Bates, 1938; Todd, 1903) appear to be different to the Botswana nodules.

The Botswana concretions have been named *Botswanella*. In the sense of the international nomenclature, this name is considered to be "open, non-nomenclatorial". The *Botswanella* nodules are concretions, apparently formed through the activity of iron bacteria which, during post-sedimentation processes, migrated into the space between selected bedding planes of the Mogobane shales.

B. THE *BOTSWANELLA* CONCRETIONS

(a) Occurrence

The following details of the occurrence in the field have been supplied by the Director of the Geological Survey of Botswana, Mr. C. Boocock, in a personal communication :

> "In one area north of Lobatsi, tuffaceous shaly, and slaty rocks, correlated with the Ventersdorp System, are characterised in certain horizons by regular almond-shaped concretionary structures, averaging about 1.25 inches in length along the longest axis, and filled with soft, red, ferruginous powdery material. They characteristically have thin skins showing striae (resulting presumably from sediments settling around them) which frequently persist and line the cavities left by the weathered out structures.
>
> "The specimens sent are possibly slightly smaller than average. The striking feature about them is their more-or-less uniform size and virtually completely uniform shape. On certain surfaces, the uniformity of shape and size of the weathered-out structures is quite striking. The rock-type in which they are found is not particularly well bedded. The bedding planes normally appear to run rather obliquely across the structures.
>
> "One of the most remarkable features about these structures is their uniform orientation, with the longer axis aligned down-dip, more-or-less parallel to the rather ill-defined bedding. Only in areas where there are local slump structures or small shears is there any orientation other than in this direction. The striae preserved in the casts are always more-or-less aligned along the length of the concretion, whatever their orientation. However, it is not always possible to separate a concretion from the enclosing shale without shattering it to the extent that the direction of striae cannot be observed. In addition, striae are not always preserved in the casts, so exceptions to the generalizations mentioned above may well occur.
>
> "With regard to a stratigraphic column of the area and the position of the Karroo System, there is no doubt that these rocks are pre-Transvaal System in age, and their correlation with the Ventersdorp System is fairly definitely established. The specimens sent come from Mogobane Dam, some 18 miles north of Lobatsi, in the extreme south-east of the Protectorate. The Ventersdorp System can be traced into the Territory from the Transvaal, some

six miles SE. of Lobatsi. In this area, the succession comprises a basal sedimentary stage of conglomerates, tuffaceous rocks, shales, and impure quartzites; an interbedded volcanic stage of rather characteristic quartz-felspar porphyries; a thick sedimentary stage of tuffaceous rocks, shales, impure quartzites, sandstones, siltstones, and conglomerates; and an upper volcanic stage of mafic amygdaloidal lava. The lava is overlain by the Black Reef Series.

"The amygdaloidal lava stage and the underlying sedimentary stage thin out rapidly when traced northwest towards Lobatsi, and at the same time the quartz-felspar porphyry thickens considerably. About four miles north of Lobatsi, the sediments overlying the quartz-felspar porphyry are developed again, and are present to the point where the Ventersdorp System strikes back into the Transvaal, north of Ramoutsa (some 30 miles north of Lobatsi). In the Mogobane area, they attain a relatively great thickness, and comprise bluish-grey, somewhat flaggy shales (in which the concretionary structures occur), impure siltstones, sandstones, grits, and conglomerates. They overlie quartz-felspar porphyry, and are unconformably overlain by the Black Reef Series. The overlying mafic amygdaloidal lava horizon is not developed in this area.

"In the Mogobane area, from which the specimens were obtained, the concretionary structures persist in a definite, relatively thin stratigraphic horizon. In this horizon, they are abundant, normally of uniform size, of uniform shape, and with a common orientation. In the shales underlying this horizon, very occasional casts are present, and the same is true of the overlying shales. These casts, however, are normally much smaller than in the main horizon. It cannot be stated definitely whether these structures persist in other stratigraphic horizons in the shale succession. Specimens of shale, with these casts have come from the area SE. of Lobatsi, but they have not been seen *in situ* in this area. In the stratigraphic horizon at Mogobane, the structures are probably even more common than indicated by the specimens sent".

(b) Morphology

The collection studied comprised nine complete specimens and twenty of more-or-less fragmentary preservations; all of them had been loosened from the rock. About one hundred other specimens are present in a second collection, more-or-less enclosed in the host-rock. Some of these are completely preserved, others are fragments or imprints only.

A certain regular symmetric shape is characteristic for all specimens; it resembles that of a tri-axial ellipsoid (Plate 1, A). The two longer axes of the bodies are oriented parallel to, and the shortest one vertical to, the bedding plane. In the following table, the dimensions of nine specimens are listed; for the tenth nodule, the lengths of two axes only were available (all data in millimetres) :

Long Axis	Intermediate Axis	Short Axis
12	6	-
14	6	5
16	9	6
20	10	7
28	13	8
28	13	10
29	14	11
30	15	12
42	22	13
44	29	14

Cut-sections oriented parallel to the axes yielded information on the concentric structure of the interior of the bodies (Figure 1). Normally, the centre is formed by a cylindrical to spindle-shaped core. In unweathered specimens, the boundary between the core and the surrounding mantle zone appears to be indistinct. When altered to a more intensively weathered condition, the material forming the central zone changes to a dark grey or yellowish powdery substance which contrasts with the reddish colour of the more solid mantle zone. In some specimens, the central zone has been weathered out completely, leaving behind a hollow (Plate 3, 2). The transverse diameter of the central zone ranges between 0.15 and 0.50 of the specimen's total diameter. The mantle zone, enveloping the central core, appears to be composed of several distinctly separate layers. The exterior layers, located towards the periphery of the mantle, may contain a number of irregularly shaped hollows which evidently are products of weathering processes. Most of the hollows appear to be lengthened in radial directions, and to be arranged along particular concentric layers (Plate 3, 1 and 2).

The outermost zone of the body is represented by a millimetre-thick coat. The surface of the layer exhibits a silver-grey, silky, delicately wrinkled relief (Plate 3, 7). The ridges and furrows of the wrinkles form a striped pattern which runs parallel to the long axis of the body. Normally, a distinct interface is developed between the coating and the adjacent rock matrix. In the vicinity of the concretions, the host-rock appears to be reddishly discoloured, forming an aureole which measures several millimetres in diameter (Plate 3, 3). The aureole changes gradually from a reddish tinge to the normal greyish colour of the rock.

(c) Analyses

Thin-sections and cut-sections were made for microscopic examination under transmitted and reflected light. Plexiglass was used as a mounting medium. The specimens studied under the electron probe microanalyzer were mounted in copper baccelit and polished with diamond powder. By use of microdrilling equipment, material was removed from specific zones within the bodies : core, mantle, fillings of the hollows, aureole, and host-rock. The samples obtained were subjected to X-ray diffraction analyses. Isolation of structured organic remains was attempted by applying two different maceration procedures : (1) treatment with HCl, HF, and HNO_3 and (2) treatment with HNO_3 and heavy liquid solution (Pflug, 1966).

All the X-ray diffractometer analyses were conducted under the same conditions. The samples used were found to have approximately the same grain-sizes. Consequently, the patterns obtained can be evaluated for qualitative, as well as quantitative, information (Figure 2). As the patterns indicate, some considerable differences exist in the composition of the different zones :

(i) The proportion of quartz is highest in the rock matrix (A); it decreases towards the central zone (E).

(ii) In contrast to the results for the rock matrix and the core, those of the mantle zones (C, D) appear to be simple : hematite is the only conspicuous component present.

(iii) The pattern of the aureole zone (B) is intermediate between that of the mantle and the normal rock matrix.

(iv) The pattern of the central zone (E) differs from all of the other zones. In its number of peaks, it resembles the rock matrix pattern, but, in contrast, quartz cannot be identified with certainty. Other differences between the central zone and the rock matrix include the montmorillonite clay minerals, which occur in the latter only. Proportions of the muscovite-sericite-illite group are significant for the rock matrix; paragonite is the only mica mineral found in the core.

The zones can be characterized as follows :

A. Rock : Fine-grained quartz occupies about 10 per cent of the matrix. In addition, considerable amounts of mica are present. As it can be seen from the position of the (060) interference at 1.518 Å both dioctahedric and trioctahedric mica types are present. Since the base interference at 10.04 Å is relatively broad, it can be assumed that all transitional members of the sequence from muscovite to hydromuscovite to illite are present. Plates of muscovite and sericite can be recognized in thin-section under polarized light. Reflexes localized at 7.13, 4.46, 3.54, and 2.55 Å possibly refer to minerals of the kaolinite group. A base reflex at 14.24 Å is characteristic of clay minerals of the montmorillonite type. Feldspars are present in small amounts only.

B. Aureole : All components found in the rock matrix (A) also occur in the aureole, but in smaller proportions. The strong peaks at 2.71 Å (100), 2.52 Å (80), and 1.70 Å (60) indicate greater amounts of hematite. The peak found at 9.71 Å is probably caused by paragonite.

C. Mantle (exterior part and coating) and D. Mantle (interior part) : The mantle consists almost exclusively of hematite. However, some accessory quartz is present in the exterior layers. It proved impossible to obtain separate material from the coating, enveloping the mantle. Microscopic examination showed that the coating normally is composed of three layers (Plate 1, B. 4-6). The exterior layer (H) consists of hematite, and the interior (Q) of quartz crystals forming a garland-shaped pattern in cross-section, these being separated by a layer (R) composed of a fine-grained substance similar to the mantle material (C). As can be observed from the X-ray images (Plate 1, B. 1-3), the areas adjacent to the contact (Z) between nodule and aureole contrast in their essential composition. The mantle (H) appears to be relatively rich in Fe and poor in Si. The aureole (B) is poor in Fe and rich in Si.

E. Central Zone : It proved impossible to identify, in thin-sections, the components of the fine-grained mineral mixture of the central zone. Polished-sections studied under the ore microscope indicated that certain amounts of hematite are present. More details were obtained from the X-ray diffraction patterns which show numerous peaks (Figure 2). The broad maxima between 3.3 Å and 3.20 Å are characteristic for the various mineral phases of the feldspar group. Besides these, there occur some which might also belong to the feldspars. However, it was not possible to identify the individual members of the feldspar group from the peaks. Probably, components of both the plagioclase and the potassium feldspar groups are present. The clay minerals of the kaolinite group are indicated by peaks at 7.2, 4.4, 2.5, and 2.36 Å. Hydrargillite is possibly present, but the coincidence of the peaks characteristic of hydrargillite with those of feldspar, paragonite, and kaolinite prevented a definite identification.

C. THE *TELEMARKITES* CONCRETIONS

(a) Occurrence and Morphology

The characteristics of *Botswanella* give rise to the conclusion that the nodules were formed by concretionary processes. Certainly, they are not the remains of an animal body or an animal skeleton. Nevertheless, the possibility exists that activity on the part of micro-organisms took part in the formation of the nodules. In fact, the maceration residue obtained from the *Botswanella* bodies yielded some evidence of this possibility.

Another factor which might speak for the organic origin of *Botswanella* lies in the apparent similarities between *Botswanella* and *Telemarkites enigmaticus* (Dons, 1959). Most investigators of *Telemarkites* tend to the opinion that these nodules were formed under the influence of algae. Other palaeontologists have considered an origin from spongi or stromatoporae colonies. Dr. J. A. Dons kindly supplied specimens of *Telemarkites*, which permitted a direct comparison with *Botswanella*.

It should be noted that a considerable time span separates the ages of the host-rocks of the two occurrences : *Botswanella* comes from rocks which are thought to be about 2300 million years old; the age of the *Telemarkites* is estimated at 800-1000 million years.

As is the case for *Botswanella*, the *Telemarkites* specimens are normally found on bedding planes, with their long axes orientated parallel, for the most part. Moreover, there are similarities in size and shape, with the minor difference that *Botswanella* resembles more the shape of a tri-axial ellipsoid, while *Telemarkites* more the shape of a bi-axial ellipsoid. Another similarity occurs in the interior structure which has both radial and concentric components. The main difference between the two types of nodules are : (1) the central core of *Telemarkites* appears to be more distinctly separated from the enveloping mantle than in the case of *Botswanella*, and (2) no structure analogous to the coating of *Botswanella* has been found in *Telemarkites* (Plate 3, 4 and 5).

(b) Analyses

Detailed microscopic and chemical analyses have been carried out by Dons (1959). Supplementary to these studies, the results of some X-ray diffraction analyses undertaken in the present investigations are shown in Figure 3. Separate samples were taken from the central zone (I), the mantle (II), and the contact of the specimen (III) and the rock matrix (IV). The results obtained show that there exist some considerable differences in the composition of *Botswanella* and *Telemarkites*.

In contrast to *Botswanella*, the patterns of the Zones I-IV of *Telemarkites* do not differ much from each other. A generally uniform mineral composition of each of Zones I-IV is indicated. The peaks, especially those of the feldspar and mica minerals, appear to be more sharply contoured in *Botswanella*. This indicates that the lattices of the *Telemarkites* crystalline phases are arranged in a more ordered condition than in the case of *Botswanella*. The differences might signify variations in the conditions under which the nodules originated. *Telemarkites* may have been formed in a thermal or hydrothermal environment, *Botswanella* under the cooler conditions of normal weathering processes.

In the main, *Telemarkites* consists of quartz and feldspars, with mica minerals of muscovite-sericitic type, in addition. Towards the central zone, the mica changes to the illitic form. Apparently, there exist similarities in the mica content of *Telemarkites* and *Botswanella*. However, they contrast in two important points : (1) *Telemarkites* lacks all clay minerals, whereas they occur in *Botswanella* in abundance; (2) *Telemarkites* contains calcite, which is not found in *Botswanella*. Thin-sections of *Telemarkites* reveal the presence of a few grains of hematite and magnetite. They are partly arranged in concentric layers surrounding the central core.

The feldspars present in *Telemarkites* have been subjected to a special study. The results obtained suggest that the feldspar peaks in the X-ray patterns indicate the presence of low-temperature albite. In the following table, the ten characteristic feldspar peaks, as found in *Telemarkites*, are compared with those published for a pegmatitic albite from Amela, Virginia (ASTM-Index, 1967), consisting of 98.2 Ab and 1.80 r.

	Telemarkites		Albite (Low-Temp.)	
hkl	d(Å)	I/I_1	d(Å)	I/I_1
001	6.36	8	6.39	20
201	4.04	40	4.03	15
111	3.78	20	3.78	25
130	3.675	25	3.68	20
112	3.50	10	3.51	10
002	3.196	100	3.196	100
022	2.94	20	2.93	15
132	2.64	5	2.64	5
241	2.56	8	2.56	7
222	1.889	8	1.889	7

Thin-section analyses of *Telemarkites* yielded additional evidence that most of the feldspar present is albite. Potassium feldspars and anorthitic plagioclases are evident in only very small amounts.

The interferences occurring in the 30 Å area (2θ = 2.3 - 2.5) are of special interest. They can be recognized in all patterns of *Telemarkites*, but appear to be especially distinct in the interior parts of the body. Probably, these peaks indicate the presence of higher molecular organic compounds (Pflug and Strübel, 1967). Under the fluoresence microscope, the areas concerned exhibit strong organo-fluorescence. It can be seen in thin-sections that part of the fluorescing substance is present in a formless condition, and that part shows distinct contours and structures, resembling organisms.

The following quantitative data have been obtained from a comparison of the *Telemarkites* patterns with those of artificial mixtures, composed of quartz, albite, muscovite, and calcite (the weight percentages given should be regarded as approximate values only) :

	Quartz	Albite	Muscovite (+ Illite)	Calcite
Core	20	50	20	10
Mantle, interior part	50	40	5	5
Mantle, exterior part	40	45	10	5
Rock matrix	35	45	15	5

(c) *Comparison Between Botswanella and Telemarkites*

The following comparison has been compiled of the mineralogical compositions of the two concretionary types :

	Botswanella	*Telemarkites*
	QUARTZ	
Core :	minor to accessory component	minor component, 20%
Mantle :	decreasing towards core	major component, 40-50%
Rock :	major component	major component, 35%
	FELDSPAR	
Core :	minor to accessory component, detailed specification impossible	low-temperature albite dominating component, 50%
Mantle :	not present	major component, low-temperature albite, 40-45%
Rock :	accessory, but not identifiable with certainty	major component, low-temperature albite, 45%
	LAYERED SILICATES	
Core :	paragonite + kaolinite, major components	minor components, 20% muscovite/sericite/illite
Mantle :	muscovite/sericite partially identifiable, montmorillonite accessory	illite/muscovite, 5-10%
Rock :	minor components, muscovite/sericite/illite kaolinite, montmorillonite	illite/muscovite, 15%
	CARBONATES	
Core :	not identifiable	calcite, 10%
Mantle :	not identifiable	calcite, 5%
Rock :	not identifiable	calcite, 5%
	ORE MINERALS	
Core :	not identifiable	not identifiable
Mantle :	hematite, major component	little hematite, magnetite
Rock :	hematite, accessory	little hematite, magnetite
	ORGANIC SUBSTANCES	
Core :	not identifiable	34 Å interference (strong)
Mantle :	not identifiable	34 Å interference (clear)
Rock :	not identifiable	34 Å interference (very weak)

D. MICROFOSSILS

(a) *Botswanella*

Crushed samples of *Botswanella* and *Telemarkites* were macerated with HNO_3 and subsequently treated with a heavy liquid solution. This method has been proved to be successful in Precambrian rocks (Pflug, 1966). The residue obtained from *Telemarkites* was found to be composed of a fine, structureless detritus; *Botswanella*, however, yielded some tiny, structured remains. Most of them have the shape of hollow globes and filamentous sheets. Since parts of these bodies appear to be coated with an ore mineral, it seems unlikely that they are recent contaminations. In a subsequent experiment, thin-sections were carefully treated with a low concentration of nitric acid, and the filamentous and globular structures became visible, enclosed in the mineral matrix (Plate 2, C). The interiors of the bodies appear to be filled with hematite. The sheets form a textile-like pattern. The globe-shaped bodies are enclosed in the sheets or attached to the sheet walls.

The structures resemble sheets of iron bacteria. There is no plausible alternative interpretation for the structures. Organo-fluorescence cannot be observed in the structures, probably because of the influence of the iron compounds which are known to counteract all fluorescence.

(b) *Telemarkites*

Structured organic remains have been detected in microscopic examination of thin-sections and polished-sections under the intensive light of a high-pressure mercury lamp. The structures recognized are extremely small. Several of the bodies (Plate 2, A) resemble the genera and species found in the Beltian System of North America (Pflug, 1965, 1968). As with the Beltian rocks, the *Telemarkites* remains usually show a three-dimensional preservation. It can be concluded from this observation that the organisms were preserved by silicification processes during their life-time or shortly thereafter. The highest concentrations of well-preserved organisms were found in the central core of the *Telemarkites* concretions. Only a few specimens were found scattered in the mantle zone, most of which appear to have been altered to pyrite.

The structures most abundant in the core are clusters of tiny globe-shaped algae which resemble the Cyanophyceae genus gloeocapsa or related groups. According to the microscopic picture, it seems as if the *Telemarkites* core was originally composed exclusively of algal colonies. The greater part was destroyed or deformed by a subsequent crystallisation phase of the chalcedons and albites.

Scattered in the core matrix, some other structured remains were detected (Plate 2, B). These are considered to be skins of one-celled planktonic organisms.

E. THE ORIGIN OF THE CONCRETIONS

(a) *Telemarkites*

According to the observations made, the concretionary nature of *Telemarkites* appears to be beyond doubt. Apparently, the formation of the nodules must have begun during sedimentation, and it seems very likely that biogenic processes were involved in their origin. The central zone of the bodies is believed to have solidified before being imbedded in the sediment, since the delicate algal colonies present in the rock matrix have preserved their perfect three-dimensional form. Most of the algae appear to be united in clusters and crowd-like colonies. This kind of arrangement gives rise to the assumption that the colonies vegetated while drifting in the sea. There is evidence that a silicification process acted upon them during their life-time.

The various studies conducted by Dons (1959) offer a reasonable explanation for the processes involved. The area of deposition was located in a shallow sea close to the coast. Calcite was the main product of deposition. Solutions from neighbouring submarine volcanoes caused silicification of the sediment. It is assumed that the drifting algae swabs were penetrated by the solutions. After their deposition, they probably became the reaction centres about which the *Telemarkites* concretions were formed. The presence of low-temperature albite seems to be especially characteristic of this kind of process. It has been suggested by Füchtbauer (1950) that the presence of this mineral in a marine environment may be due to reaction of siliceous solutions with sea water.

The observations relating to *Telemarkites* resemble, in some respects, those made on the Molar Tooth Limestone of the Beltian System. As with *Telemarkites*, the Beltian biologic remains appear to be enclosed three-dimensionally in a silicified lime matrix. In addition, in both types, certain amounts of albite are found in the rock matrix. However, there exists a considerable difference in the morphology of the structures. In contrast to the nodule shape of *Telemarkites*, the Molar Tooth structures consist of fine-layered rug or umbrella-shaped elements, which are similar to stromatolite structures. The difference may be due to the types of organisms responsible for the formation of the rocks. The organisms characteristic of the Molar Tooth Limestone represent the filamentous type of stromatolitic algae, which, united in colonies, probably covered the bottom of a shallow sea. Planktonic globe-shaped type organisms are found in *Telemarkites*.

(b) Botswanella

Certainly, *Botswanella* is a concretion. According to the organic structures detected in the matrix, it seems likely that iron bacteria played a part in the formation of the nodules. There is some evidence that, in contrast to *Telemarkites*, the *Botswanella* concretions were not formed at the time of sedimentation, but are the products of subsequent deformation of the host-rocks. The orientation of the nodule axes usually corresponds with that of such tectonic features as cleavage, the striation pattern visible on the bedding planes, and the arrangement of the sericitic sheets.

In the field, it was noted that most of the long axes of the concretions are oriented in a NW.-SE. direction. A group of lineations and joints visible on the bedding planes runs in the same direction (Plate 3, 8). Usually, the *Botswanella* bodies are aligned along these lineations. In several places, it was observed that the lineations have been distorted by the growth of the nodules (Plate 3, 6 and 9). Consequently, the concretions must be younger than the phase of deformation which caused the lineations. A second joint system, crossing the older structures at an obtuse angle, cuts and splits the *Botswanella* concretions (Plate 3, 6 and 9), and is later in age than the concretions. The following personal communication was received from Mr. R. N. Crockett, of the Geological Survey of Botswana :

> "Tectonic Environment : Long axes of concretions are orientated in an approximately southeast direction. This coincides with the direction of major gravity gliding in this district during post-Transvaal System, pre-Waterberg System times. During this period of gravity gliding, it is probable that a certain amount of relative bedding plane slip took place in the Mogobane shales".

It follows that the *Botswanella* concretions could have been formed, if they are related to the one set of joints, between 1500 and 2000 million years ago. Thus, they are considerably younger than the Ventersdorp host-rocks. The origin of the *Botswanella* nodules can be interpreted as commencing with the tectonic processes operative during post-Transvaal and pre-Waterberg time, which were initiated by gravitational gliding along bedding planes. The spaces opened by such movement were penetrated by groundwater carrying iron and iron bacteria. Iron compounds, precipitating from the solutions, formed thin layers which are still preserved, covering the bedding planes. Through some form of subsequent reactivation, certain of the iron layers were transformed to nodules (Plate 3, 3). It is suggested that these processes resulted from the reciprocal reaction of reducing effects, initiated by organic material in the shale matrix, on the one hand, and of the oxidizing activity of the iron bacteria, on the other hand.

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KEY TO PLATES AND FIGURES

Plate 1

A : Specimens of *Botswanella*, isolated from the rock matrix. Scale in millimetres.

B : Cross-sections through the exterior zones of *Botswanella*, as observed under the X-ray microprobe analyzer (B. 1-3) and in thin-sections under transmitted light (B.4-6).

B.1 : Composition scanning image. A joint (Z) separates the aureole (B) from the hematite garland (H).

B.2 : X-ray scanning image for iron.

B.3 : X-ray scanning image for silicon.

B.4 : Thin-section showing the following zones : mantle (C), quartz garland (Q), intercalated iron-rich layer (R), hematite garland (H), aureole (B).

B.5 : Quartz garland, intercalated layer and hematite garland shown in greater magnification.

B.6 : Hematite garland shown in greater magnification.

Scale for B. 1-3 : See under B.2
Scales for B.4-6 : Below the photographs
Scale distances = 10 microns.

Plate 2

A and B : Microfossils photographed in rock sections of the core zone of *Telemarkites enigmaticus Dons*. The specimens shown in A are colonies of globe-shaped algae; in B, photographs are of one- or two-celled bodies.

C : Structured organic remains, resembling sheets of iron bacteria, visible in thin-sections of *Botswanella* after maceration with HNO_3.

Magnification = 3000x
Distance between scale marks = 10 microns

Plate 3

1 : *Botswanella*, section parallel to the long axis.

2 : *Botswanella*, cross-section.

3 : *Botswanella*, embryonic specimen.

Magnification, 1 - 3 = 1.5x
Scale above 2 shows millimetres.

4 and 5 : *Telemarkites enigmaticus Dons*, sections oblique to the long axis.

Magnification, 4 and 5 = 3x
Scale below 5 shows millimetres.

6 - 9 : Occurrences of *Botswanella* on the bedding planes of the Mogobane shales.

6 : A joint of an older tectonic system, running from left to right, above the coin, has been laterally deformed by a *Botswanella* concretion. The joint of a younger system, left of the coin, cuts a *Botswanella* concretion.

7 : *Botswanella* specimen, partly broken, showing an interior consisting of hematite.

8 : *Botswanella* concretions located on the lineations on bedding planes.

9 : Joint of a younger tectonic system cutting a *Botswanella* concretion.

Figure 1 : Sketch showing cross-section through *Botswanella*. A = rock matrix, B = aureole, C = exterior layers of mantle, D = hollows of the interior mantle layers, E = central zone, Q = quartz garland, H = hematite garland.

Figure 2 : X-ray diffraction patterns obtained from zones A-E of *Botswanella*. F = feldspars, Hy = hydrargillite, Mo = 14 Å clay minerals (montmorillonite, chlorite, sudoite), M and M/I = muscovite or sericite or 10 Å clay minerals (hydromuscovite, illite), K = 7 Å clay minerals of the kaolinite group, H = hematite, P = paragonite.

Figure 3 : X-ray diffraction patterns obtained from zones I-IV of *Telemarkites enigmaticus Dons*. The sketch above pattern IV shows the location of zones I-IV in a cut-section oblique to the long axis. The identification of the peaks is the same as for Figure 2, plus C = calcite, O = organic compounds.

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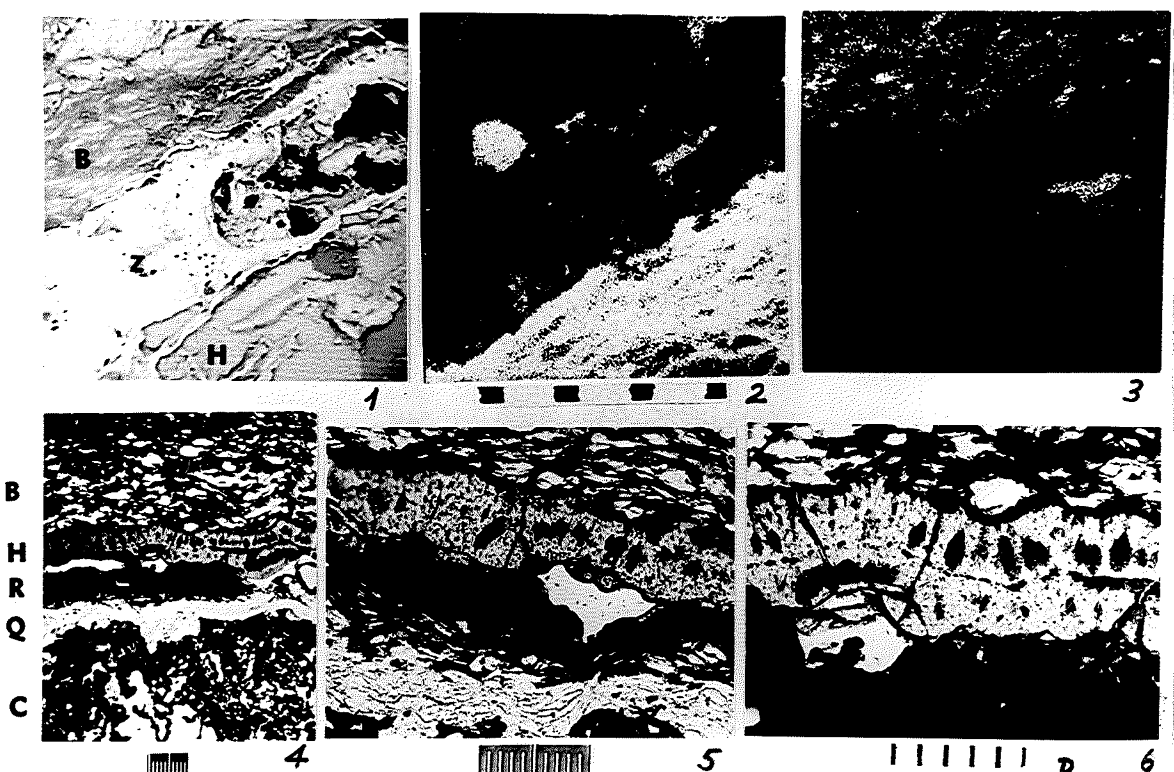

PLATE 1

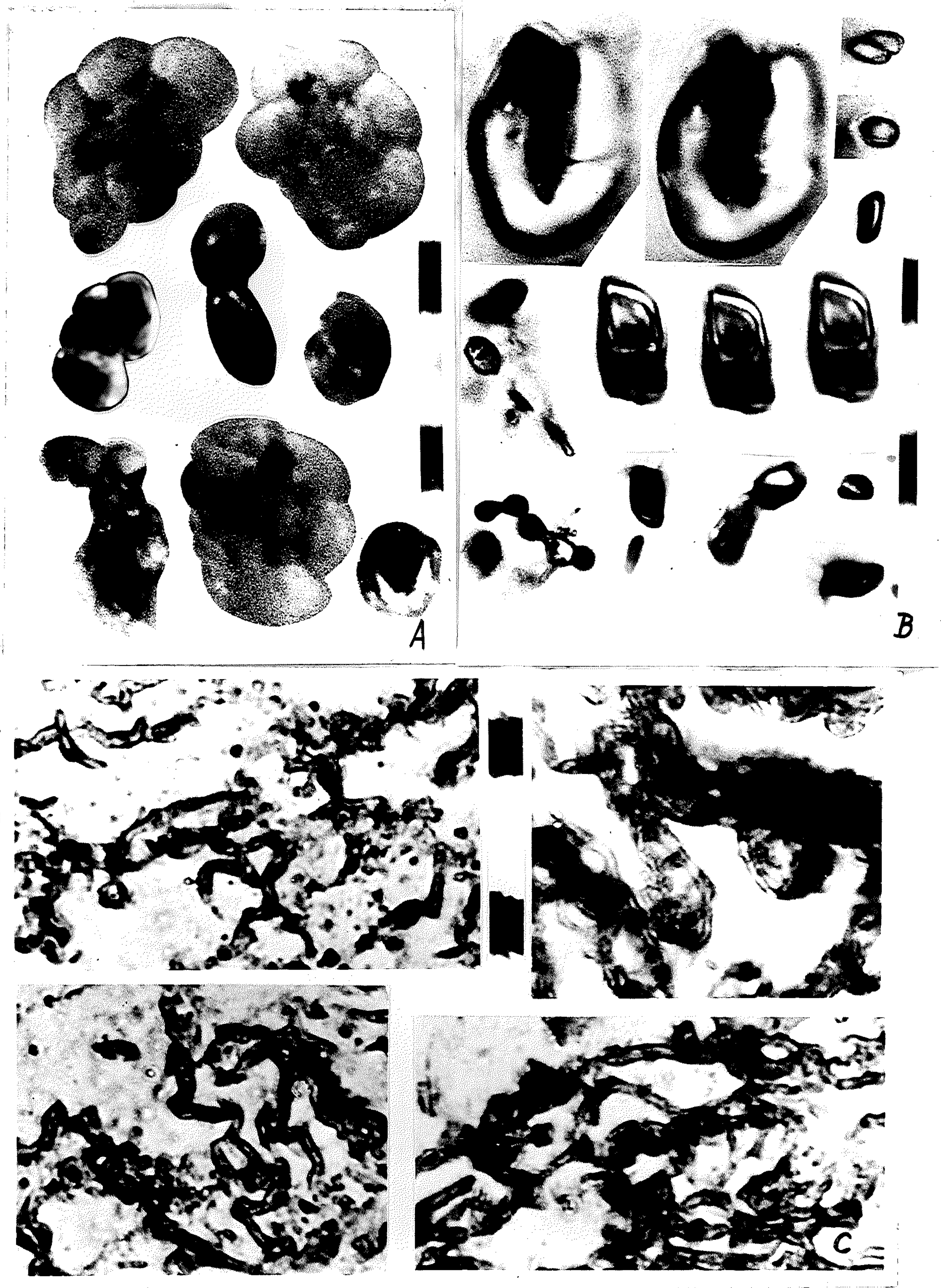

PLATE 2

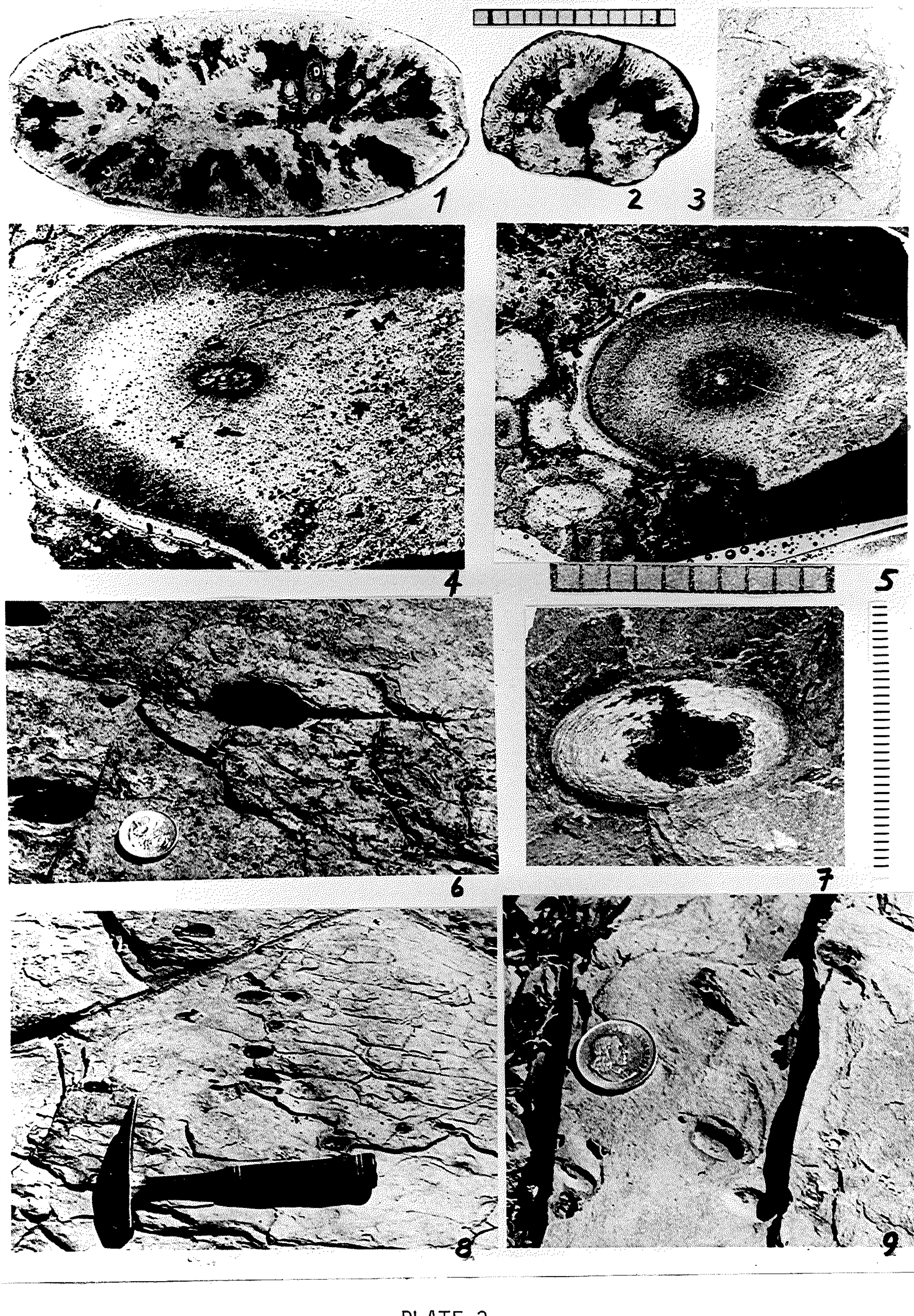

PLATE 3

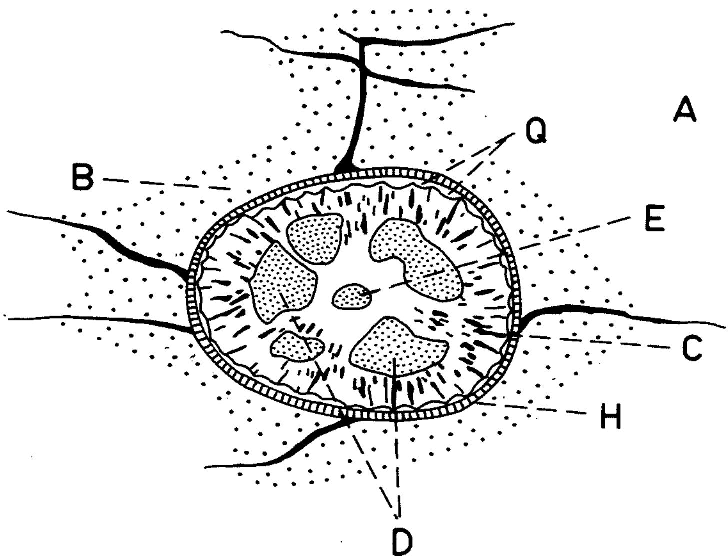

FIGURE 1

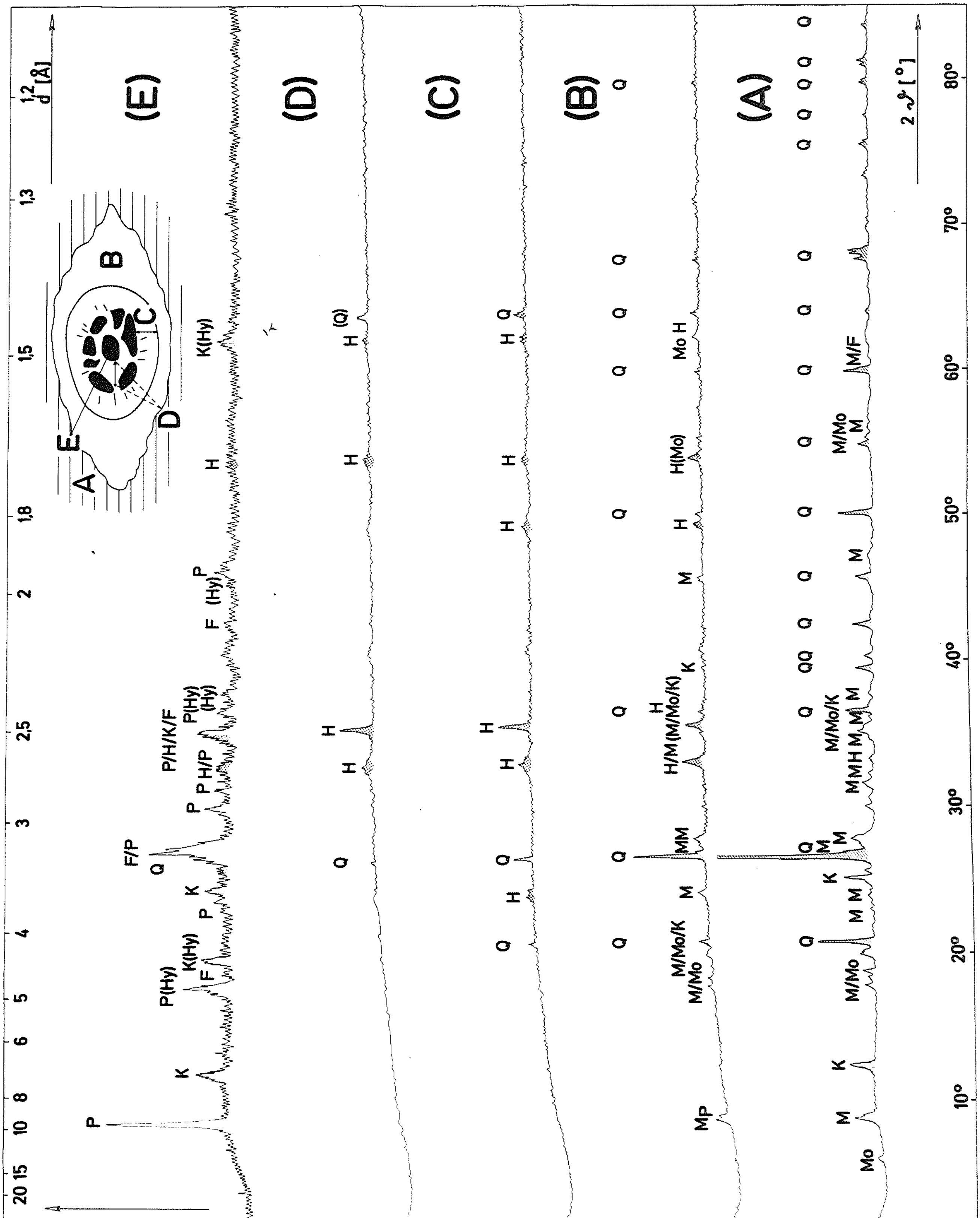

FIGURE 2

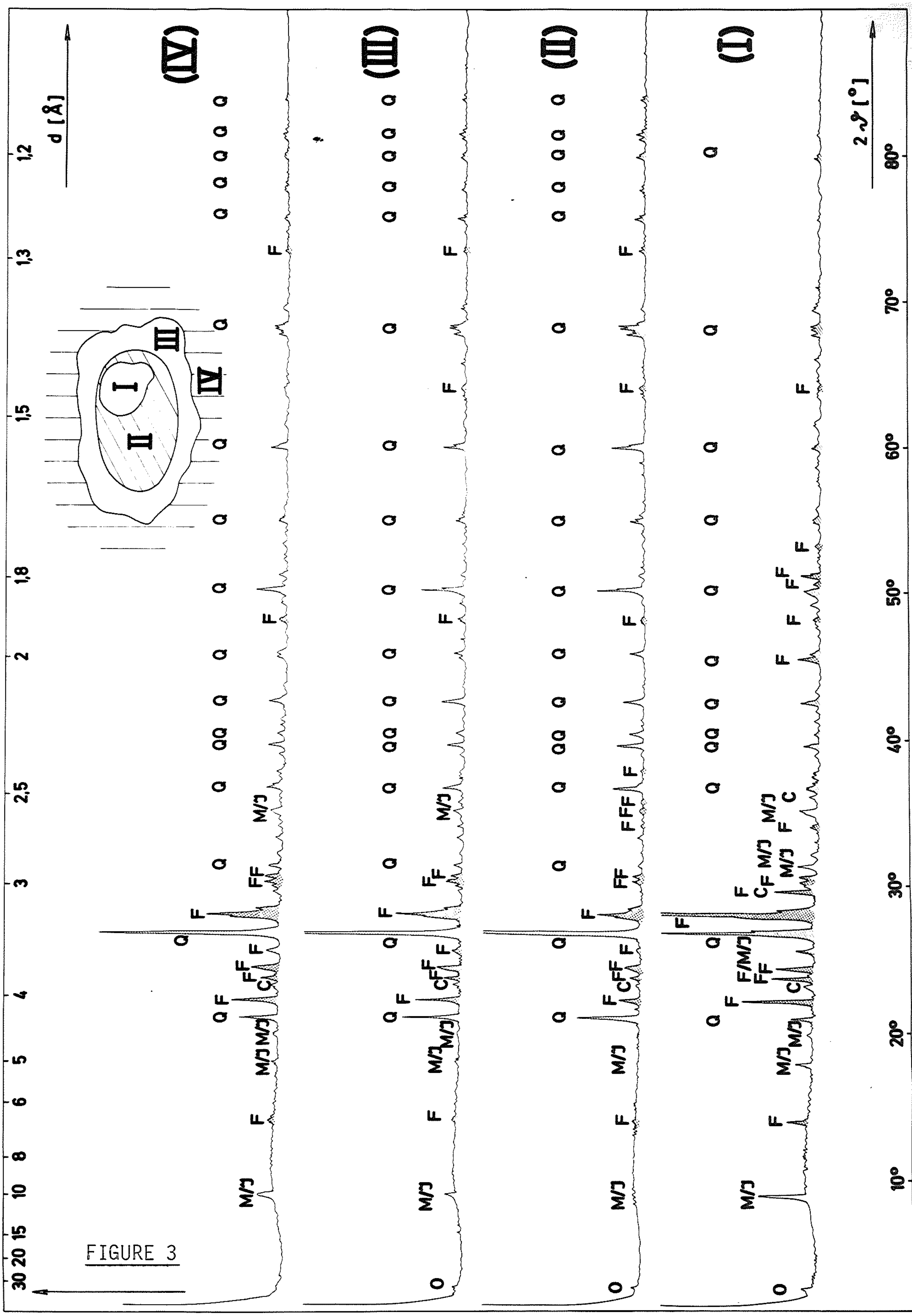
d [Å]
2ϑ [°]
(I)
(II)
(III)
(IV)
I
II
III
IV
30 20 15 10 8 6 5 4 3 2,5 2 1,8 1,5 1,3 1,2
10° 20° 30° 40° 50° 60° 70° 80°
Q
F
M/J
C
O

FIGURE 3