Geology and Utilization of the "Pugu Hills" Kaolin Deposit, Tanzania

by

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With
3 Text-Figures, 8 Plates and 1 Table

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Summary

Under a consultancy agreement concluded with State Mining Corporation of Tanzania, in 1980/81, AUSTROPLAN, Austrian Engineering Co. Ltd., carried out a feasibility study with the objective of investigating the techno-economic aspects for the exploitation of Pugu Hills Kaolin Deposit on an industrial scale. Based on extensive geological field surveys, mapping of the existing underground workings, and on the core descriptions, using up-to-date mineralogical methods, a better understanding of the sedimentary environment and the genesis of the extensive deposit was achieved.

The predominant kaolinitic raw material is represented by clayey-silty sandstones of two main types. As indicated by Scanning Electron Microscope analysis the kaolin "Type C and K" of previous reports, clearly turns out to be of in situ genesis, most probably formed by weathering of feldspathic sandstones and – more rarely – of highly feldspathic fine-grained sediments. Cross-bedding, scour and fill structures, root-moulds, with in part preserved root substance, occasional stringers of very coarse sand grains or pebbles, mottling and bleaching along fissures and rootlet tubes due to secondary reduction of Fe^{3+} to Fe^{2+} are the more conspicuous sedimentary features. On the other hand, kaolin "Type D" is in general more massive and, except

for occasional root canals and staining and scattered stringers of coarse-grained quartz, completely lacks the sedimentary structures mentioned above. Occasional pebble conglomerate beds, up to about 1 m thick, indicate lags of deposition. We consider the sediments of Pugu Kaolinitic Formation to be deposited in an upper deltaic environment, most probably under entirely freshwater conditions – by a Miocene "Pre-Ruvu River". While "Type D" is considered to represent channel deposits, with kaolin transported from a hinterland, kaolin "Type C and K" is considered to have developed in situ in various backswamp or respectively interdistributary environments of the delta plain. As a probable source area, indicated by heavy mineral analysis and the inferred paleodrainage configuration, the crystalline basement of the Uluguru Mountains, the Karroo at Mvuha (as documented by gravel lags in the channel deposits) and eluvial and alluvial deposits must be taken into consideration.

In view of the comparatively thin overburden cover, the kaolin deposit in the area investigated can be worked by open pit. Due to wide variations in quality of the raw material, a selective mining technique is imperative. Employing a conventional process flow-sheet, kaolins of favourable ceramic properties and a good quality filler-grade kaolin can be obtained well suited to the production of paper, rubber and paints as well as pesticides. Quartz sands discharged as process tailings can basically be used as foundry-, building-, and glass sand.

Zusammenfassung

Im Rahmen einer Zusammenarbeit zwischen der State Mining Corporation, Dar es Salaam, und AUSTROPLAN, Wien, wurde in den Pugu Hills (Tansania) ein Kernbohrprogramm zur Rohstoffsicherung für einen geplanten Kaolin-Tagebau, der auf eine Werkskapazität von rund 110.000 Tonnen/Jahr Rohkaolin ausgelegt sein soll, mit positivem Erfolg durchgeführt. Aufgrund der geologischen und mineralogischen Untersuchungen der Bohrkerne sowie ergänzender Feldstudien und Befahrungen der Untertagebaue, konnten Hinweise zur Genese der Kaolinlagerstätte gefunden werden.

Zwei Rohmaterial-Haupttypen, beide kaolinführende tonig-siltige Sandsteine, können mit mineralogischen Methoden unterschieden werden; sie sind jedoch häufig im Handstück nicht eindeutig identifizierbar. REM-Fotos zeigen im Rohmaterial, das in früheren Berichten als Kaolin "Typ C bzw. K" bezeichnet wurde, schöne Kaolinitstapel mit idiomorphen pseudohexagonalen Kristallen. Sie deuten klar auf in situ-Entstehung hin. Die wichtigsten Sedimentstrukturen sind Kreuzschichtungen, Erosionsstrukturen, untergeordnet Schnüre von Grobsand oder Kies, Wurzelröhren mit z. T. erhaltener Wurzelsubstanz, vielfarbige fleckige Verfärbungen, sowie Bleichungszonen entlang von Klüften und konzentrisch um Wurzelkanäle. Der Kaolin "Typ D" ist im allgemeinen massig ausgebildet und zeigt, ausgenommen von gelegentlichen Verfärbungen und vereinzelten Schnüren von Grobsand und Kies, sowie sehr selten Wurzelkanälen, keine der oben angeführten Sedimentstrukturen. Im REM zeigt sich ein wirres Gefüge unregelmäßig begrenzter Kaolinitblättchen. Gelegentlich sind bis nahezu 1 m mächtige konglomeratisch verfestigte Kieslagen zwischengeschaltet; sie sind klar als Residualkonzentrate erkennbar.

Hinsichtlich der Bildungsbedingungen dürften die Gesteine der "Pugu Kaolin Formation" in einem am Festland gelegenen fluviatilen Deltabereich abgelagert worden sein, der vermutlich durchwegs oberhalb der marinen Beeinflussung lag. Während die Sedimente des Kaolin "Typ D" sehr wahrscheinlich umgelagerte, ferntransportierte

kaolinführende Sandsteine darstellen, die als Rinnenfüllungen des Flußbettsystems eines miozänen „Prä-Ruvu-Flusses" anzusehen sind, stellen die Kaolinite des „Typ C/K" in situ aus Arkosesandsteinen verwitterte Sedimente dar. Ihr ursprünglicher Ablagerungsbereich ist in den Überschwemmungsgebieten im nicht marin beeinflußten Flußdeltabereich zu suchen. Als Hinterland für diese terrigenen Schüttungen kommt das gesamte westlich der Pugu Hills gelegene Gebiet in Frage. Schwermineraluntersuchungen machen eine Herkunft aus dem Grundgebirge der Uluguru Berge wahrscheinlich. Doch auch die Karroo-Bildungen bei Mvuha führen feldspatreiche Gesteine, und glaziale Diamiktite der Karroo könnten als Lieferanten der gut gerundeten Quarzkieslagen, die als Flußrinnen-Residualsedimente den kaolinitischen Sandsteinen vom „Typ D" zwischengeschaltet sind, in Frage kommen. Außerdem müssen als Herkunftsgebiet der transportierten Kaoline vom „Typ D" auch noch eluviale und alluviale Ablagerungen in Betracht gezogen werden.

Für die bergmännische Gewinnung der oberflächennahen Lagerstättenteile im Untersuchungsgebiet bietet sich die Betriebsart Tagebau an, wobei angesichts der Qualitätsschwankungen des Rohmaterials selektiver Abbau erforderlich ist.

Aus dem Rohkaolin lassen sich durch herkömmliche Naßaufbereitung Kaoline mit guten keramischen Eigenschaften und Füllstoffe für die Papier-, Gummi- und Farbenherstellung, sowie Trägerstoffe für Pestizide erzeugen. Aber auch der anfallende Quarzsand ist als Gießerei-, Bau- oder Glassand verwendbar.

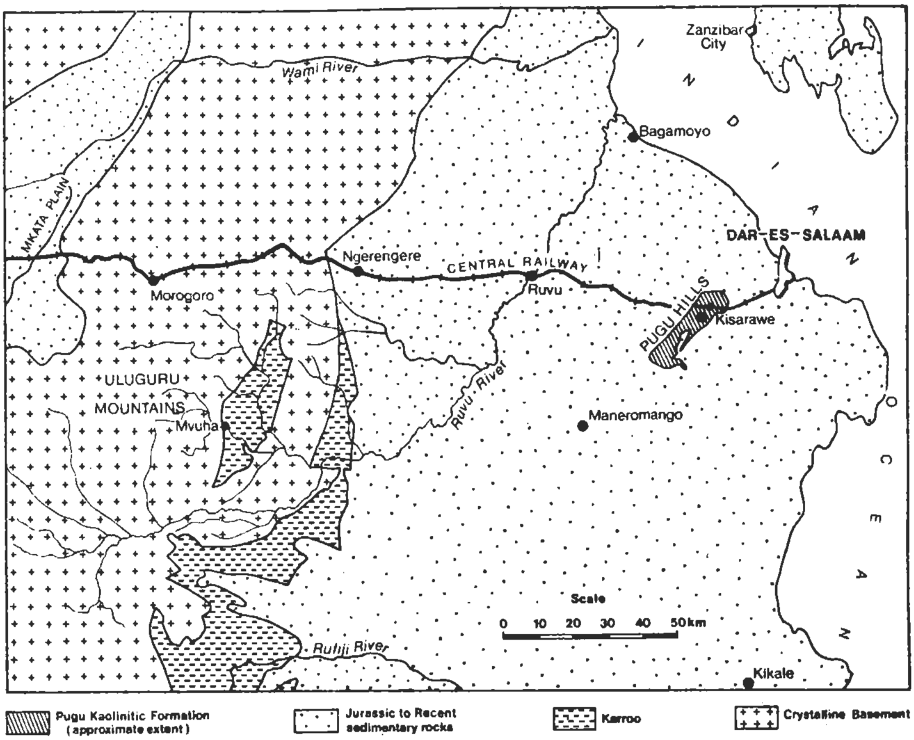
1. Introduction

Wilhelm BORNHARDT, the famous German geologist and explorer of the former "Deutsch-Ostafrika" (German Colony of East Africa), reports in his diary on February 16, 1897 that he discovered "snow-white soils and whitish kaolinitic sandstones" in the Pugu Hills close to the Kisarawe mission (BORNHARDT 1900). However, commercial exploitation did not start before 1942. Various mining companies in succession mined small quantities of raw kaolin from underground workings and produced washed kaolin of the order of several hundred tons per year. In 1976 the property was acquired by STAMICO, State Mining Corporation. A continuous rising demand for kaolin products made it desirable for STAMICO to investigate the possibility of setting up a new open pit mine and processing plant.

Following an official request by the Ministry of Finance and Planning of the United Republic of Tanzania, funds were granted by the Austrian authorities under the Technical Aid Program (Bundeskanzleramt, Project No. 796/80) to study the feasibility of the project. Under a consultancy agreement with STAMICO, AUSTROPLAN – Austrian Engineering Co. Ltd. – was entrusted with its implementation and overall coordination. The mineral-specific industrial know-how was provided by Messrs. KAMIG, an Austrian kaolin mine and plant operator. The geological field investigations were conducted by a geologist of the Austrian Geological Survey, while mineralogical investigations were carried out at the Institute for Soil Science and Engineering Geology, University of Agriculture, Vienna.

Because of the project area's proximity to Dar es Salaam (Text-Fig. 1), to which it is linked via main highway to Kisarawe and by the Central Railway Line, the target area is favourably located and all basic infrastructural requirements for the establishment of a major industrial enterprise are met.

Up to 1980, mining took place in two areas, i. e. in the immediate surroundings of



Text-Fig. 1: Simplified geological sketch showing approximate extension of Pugu Kaolinitic Formation in relation to the hinterland (after KENT et al. 1971).

the kaolin plant and more recently at Mambisi, some 2 km distant to the west. Both areas were worked by underground methods, each being characterized by a kaolinitic raw material with specific properties. The reference paper reviewing the geological framework is by TRUTER 1952. The kaolin sandstone in the collapsed Mambisi underground workings is designated "Pugu Type C or K" in former reports, at the kaolin plant it is referred to as "Pugu Type D". Additional mineral specific characterization was reported by ROBERTSON et al. 1954.

The scope of this paper is to discuss the results of purely scientific interest and to enable comparison of these data with other kaolin deposits of sedimentary origin, e. g. in the southeastern United States, England, and Bavaria. It is therefore not our intention to report on techno-economic parameters governing the feasibility of the project.

We thank STAMICO and the Austrian authorities for permission to publish some of the findings made during the course of this study.Throughout the execution of the project, STAMICO contributed substantially by furnishing a large part of the basic input data for the study as well as the dedicated services of its well-trained drilling staff. While it would be impossible to mention all individuals who participated in the execution of the project, it is imperative to gratefully acknowledge the support and cooperation of Mr. W. H. MANNING, General Manager of STAMICO and his executives S. L. BUGAISA, A. G. MUSHI, E. OLE NAIKO, C. K. TOLAGE, E. W. JENGO, P. SELEKA, M. WOLFE, as well as the special consultant H. ALLENIUS.

2. Geology

2.1 Previous Research

In some of the following chapters ample reference is made to previous literature. In these paragraphs, therefore, only a few additional remarks are made. All publications and unpublished reports concerning Pugu kaolin, which were studied in the respective libraries of STAMICO-headquarters in Dar es Salaam and in the Geological Survey of Tanzania in Dodoma, are quoted in the bibliography at the end of this paper.

Apart from the topics of stratigraphic age, sedimentary environment, structural geology and various mineralogical aspects, a number of papers concern themselves mainly with the economic potential of Pugu kaolin deposit. The reserves of raw kaolin, located above the railway level, were calculated by TRUTER 1947 to be in the range of 2 billion tons; CILEK's 1979 estimate is of the order of 1 billion tons. Other reports provide figures not comparable to those mentioned previously, because they consider only a preselected area (e. g. SERI-Renault 1967, OHARU et al. 1974, MUSHI 1980, AUSTROPLAN 1981). Without doubt, Pugu kaolin deposit is one of the largest known in Africa, perhaps even in the whole world, and from the point of view of reserves could be mined at any desired scale.

It is imperative in this context, to mention the diverse activities by BP–SHELL in the Pugu Hills. Apart from successful geological field programs, including core drilling, several geophysical surveys were also carried out (e. g. SUTHERLAND 1956, KIRKALDY 1961, PRATT 1962). A concise review of all relevant data was compiled by KENT et al. 1971.

2.2 Review of the Geology of Pugu Hills

2.2.1 General Remarks, Geological Setting

The best review of the geology of Pugu Hills and surrounding areas was given by KENT et al. 1971. BARTHOLOMEW 1963 provides a precise geological map at the scale of 1:125.000 (Quarter Degree Sheet 186: Dar es Salaam), with a brief but outstanding explanatory text. An excellent compilation of most of the literature concerning kaolin in Tanzania is given in the paper by CILEK 1979. These three papers provide the information required for a basic understanding of the geological framework described in the following paragraphs.

The coastal area of Tanzania is unique within East Africa, in showing an almost complete stratigraphic sequence on top of the crystalline basement complex ranging from Karroo to Recent times, permitting analysis of the development of the continental margin in terms of sedimentation, marine incursions, local warping and the dating of fault movements (KENT et al. 1971). The geological history of this area should be seen as being closely related to the East African Rift Valley and its development through time and in relation to the history of the Indian Ocean. A west-east-section, from the basement of the Uluguru Mountains to the shore of the Indian Ocean, shows that the sedimentary cover gets younger towards the east. A short review of the western hinterland of Pugu Hills is provided in chapter 2.4 "Provenance of Pugu Kaolinitic Formation".

2.2.2 Stratigraphy

Ever since the time of the German administration (BORNHARDT 1900), the stratigraphic age of Pugu Kaolinitic Formation has been a matter of discussion. Due to the apparently complete absence of fossils, it has not been possible up to now to date the formation exactly by a direct method. We have also made many attempts to date the sequence stratigraphically – unfortunately without any success. A larger set of samples from greenish "claybound sands" and soft kaolinitic mudstones was washed, and examined for microfossils and we also checked for pollen and spores. One of these preparations, taken from weathered greenish clays along Central Railway Line, shows extremely poor preserved palynomorpha; perhaps fresher samples could provide more adequate material. As might be expected, the tests for nannofossils were also not successful. In this context, we wish to thank Dr. Ilse DRAXLER and Dr. Herbert STRADNER (Geological Survey of Austria, Vienna) for analysing the samples.

BORNHARDT 1900 compares the kaolinitic soils and sandstones close to Kisarawe mission with the Mikindani Formation of southern Tanzania and proposes an uppermost Tertiary age. RECK & DIETRICH 1921 studied samples from railway cuttings west of Pugu Station and stratigraphically assigned – what they called "Pugu Sandstone" – with some reservation to the uppermost Cretaceous. An important discovery was made by geologists of BP–SHELL (reviewed in KENT et al. 1971), who found an abundant marine fauna of Lower Miocene age, mixed with Paleocene faunal elements, in the immediately underlying beds. These data were obtained from cores of Pugu No. 2 borehole, mainly based on microfossils of "Pugu Spatangid Shales". This suggests, that the beds under consideration are not older than Lower Miocene and most probably comprise Miocene, perhaps even up to Pliocene age.

MUSHI 1980 reports an interesting find of a specimen of the marine pelecypod *Pectunculus* in kaolinitic sandstones. Though this fossil is most probably not stratigraphically indicative, its examination by an experienced paleontologist would be most desirable particularly because of paleoenvironmental considerations.

2.2.3 Structural Geology

In the Pugu Hills there are many structural features which can easily be recognized during the course of geological fieldwork and from core descriptions. However, the interpretation of the various scattered data obtained proves to be a rather difficult task. Fortunately BP–SHELL conducted a series of geophysical surveys comprising aeromagnetic, gravity and seismics and in addition drilled two boreholes close to Pugu Railway Station. These data are reviewed and discussed in the excellent paper by KENT et al. 1971.

The fundamental relationship between tectonics and sedimentation is the basis for the understanding of the Tanzanian coastal belt and of the Pugu Hills in particular.

The general strike direction of the Pugu Kaolinitic Formation runs almost parallel to the present adjoining coast line of the Indian Ocean, i. e. in a NNE/SSW-direction. This is also the main fault direction bordering the cuesta scarp of the Pugu Hills to the east and their less pronounced cuesta backslope to the west. The formation of Pugu Hills cuesta is most probably due to the postdepositional upthrust to the east and a tilting of the whole fault-block mountain to the west. Block-faulting, caused by en echelon faulting appears to be the best explanation for the repetition of Pugu

Kaolinitic Formation and "clay-bound sands", as exposed in the cuttings of the Central Railway. In addition to the major strike direction of the fault system, a second important fault line trend has a NW/SE direction. These minor faults are considered to be younger (HOROBIN 1957) and break the Pugu Hills into a series of blocks.

HOLROYD 1954 and HOROBIN 1957 also discuss if the present Pugu Hills could represent an anticline; the NNE/SSW fault line would then correspond closely to the axial surface trace of the original structure, the eastern flank of which was downfaulted below the present Dar es Salaam coastal plain. If, however, the Pugu Hills is a tilted fault block, the fault line could represent the "hinge" axis of the movement, all the tilting being to the west. As pointed out above, the latter explanation is emphasised in this paper.

Faulting is clearly proven by the two boreholes drilled by BP—SHELL close to Pugu Railway Station. The off-set of strata in the eastern drillhole amounts to more than 300 meters, the distance between the two boreholes being only 230 meters. Further profound discussions of the evidently close relationship between tectonics and the history of regressions in Tanzania were provided by KENT et al. 1971.

The field exposures show a variety of minor structures. A system of joints and fractures, vertically cut both the arenaceous and argillaceous sediments, the latter often slickensided (see also HOLROYD 1954). The area investigated has shallow dip-slopes towards the west (Plate 8, Fig. 2). This direction cannot reflect the original dip direction of the strata, because the general drainage and therefore the major dip-direction was in an easterly direction. These reverse dip-directions can be explained as due to a tilting of fault bounded blocks towards the west.

2.3 Mineralogy and Sedimentary Petrology

2.3.1 Preliminary Remarks and List of Samples

The present paper attempts to examine the mineralogical composition and the microfabric of kaolinitic sedimentary layers, in order to obtain further definitive information on the deposit's genesis supplementing the results of the field investigations and the interpretation of the cores.

The mineralogy of Pugu Kaolinitic Formation has been the subject of a number of papers. Kaolin exploitation by the South African mining company "New Consolidated Gold Fields Ltd.", Johannesburg, resulted in an intensive analysis-program (TRUTER 1947, 1952, BRINDLEY & ROBINSON 1947, MELDAU & ROBERTSON 1952, ROBERTSON et al. 1954); this led to the identification of two main kaolin types. In brief, the reports mentioned above, indicate that Pugu "Type C and K" ("soft kaolin") show excellent whiteness and a kaolin content of approximately 30 %, the sandgrains being of a narrow size range, with a median diameter of 0,28 mm. The kaolinite is well crystallized, structurally more perfect, but imperfect in crystal shape. On the other hand, Pugu "Type D" ("hard kaolin") is less white, with a higher kaolin content, sometimes up to more than 50 %, the sand grains having a much wider size-range with a median diameter of 0.18 mm. The kaolinite crystals of Pugu "Type D" are euhedral, very well crystallized, morphologically perfect (ROBERTSON et al. 1954, CILEK 1979).

In practice, however, the division into these two types is valid for the area of the two underground workings only. Field data and the cores of STAMICO/AUSTRO-

PLAN core drilling program show that there exists a gradual transition with respect to grain sizes of the sand fraction, as well as in the mineralogy of the clay fraction.

Further mineralogical investigations were carried out by a number of consultants. For instance, the report by SERI-Renault 1967 provides electron microphotographs. OHARU et al. 1974 report on the presence of montmorillonitic sandstones and the report by HILLS 1962 and by the Ministry of Mines (ICEMIN) 1970 provide extensive data on mineralogy and chemistry. The heavy mineral content has already had considerable attention, e. g. in the papers by GUEST 1949, McKIE 1955, and AUSTROPLAN 1981.

While a large number of samples was collected and analysed during the course of AUSTROPLAN's investigations, the list presented below contains only those samples to which special reference is made in the text and the illustrations of this paper.

PU 1: Greenish clayey-silty arkose sandstone; approximately 100 m east of eastern entrance to the abandoned railway tunnel at Pugu kaolin plant; roadcut in lower bend of access-road to STAMICO/AUSTROPLAN drilling area.

PU 11: Greenish claystone; clay-pit at SIDO tiles and brick plant, about 1 km east of Pugu kaolin plant.

PU 16: Redbrown arkose sandstone; small quarry on road from Kisaware to Kazimzumbwi village, immediately north of Zumbwi River bridge.

PU 23, PU 24: Kaolinitic clayey-silty sandstone of collapsed Mambisi underground mine; characteristic of "Type C or K" kaolin.

All sample-numbers beginning with "AP" are from STAMICO/AUSTROPLAN-drillholes; e. g. AP 1/23,6 refers to: borehole AP 1, depth 23,6 m.

2.3.2 Methods

The mineral content of crude rocks was analysed in ground samples by x-ray diffractometry, using a Philips x-ray diffractometer (radiation CuKα, 40 kV, 20 mA).*) The quantitative determination of the quartz content was carried out by binding the rock powder with a synthetic resin. After hardening the sample was again homogenized, by grinding into a powder.

For the grain size fraction $<$ 2 microns the clay mineral content was determined by x-ray diffractometry. This clay fraction was separated by sedimentation method, after suspension in H_2O_2 and additional ultrasonic treatment. For x-ray analysis, the prepared samples were coated with K- and Mg-ions. In addition, the prepared textures were measured for expansion, using glycerine and dimethylsulfoxide (DMSO).

The quantitative determination of the mineral distribution was established by comparison of reflex intensities, using correction factors which were determined by theoretical and experimental means.

Employing a Cambridge Electron Microscope "Stereoscan S 6" **), microfabric and microchemical analyses, partly supported by Energy Dispersive Analysis of x-ray (EDAX), were carried out. For this purpose, undisturbed samples, after sputtering with gold, were used.

The mineral assemblage and the fabric of a number of selected rock types were also studied under the polarization microscope.

Grain size analyses were carried out by wet screening and by the sedimentation method after Andreassen in the laboratories of KAMIG.

*) Fonds zur Förderung der wissenschaftlichen Forschung in Österreich, Project No. 1613.
**) Fonds zur Förderung der wissenschaftlichen Forschung in Österreich, Project No. 1617, 4264.

TABLE 1

Sample No.	MINERALOGICAL ANALYSES REL. % Total Mineral-content			Clay Minerals <6 μ			Clay Minerals <2 μ				Ratio Quartz/Kaolinite <25 μ		Grain size analyses, weight %				SEM	Thin section
	Q	K	O	K	S	I	K	S	I	O	Q	K	>2,0 mm	2,0 - 0,063 mm	0,063 - 0,002 mm	<0,002 mm		
PU 1	29	K	F,M,S	63	37	Tr	17	71	12								+	+
PU 11	8	K	F, M	100		Tr	Tr		86	ML 14 C Tr								
PU 16																	+	+
PU 23																		+
PU 24	57	43		100		Tr	100										+	
AP 1/23,6											48	52	0,5	47,4	24,0	28,1		+
AP 1/55,2																	+	+
AP 2/50,2													2,0	57,2	20,2	20,6		+
AP 2/58,0	64	36									50	50	–	36,0	26,5	37,5		
AP 3/8,21																	+	+
AP 3/24,75	53	47		100			Tr				1	99	–	56,0	26,1	17,0	+	
AP 4/9,05													0,2	66,2	33,6	n. d.		+
AP 4/42,5											39	61	–	53,7	46,3	n. d.		+

AP 5/35,55	74	26		100		Tr	100				44	56	–	51,6	21,9	26,5		
AP 6/26,5											37	63	–	50,5	27,9	21,6	+	
AP 6/51,25											51	49	0,1	59,9	18,9	21,1	+	+
AP 6/59,6	45	55									8	92	0,1	44,5	28,0	27,4		
AP 7/26,8											48	52	–	54,2	22,1	23,7	+	
AP 7/37,0											51	49	–	50,2	24,9	24,9	+	
AP 7/48,0											43	57	–	45,9	28,1	26,0	+	
AP 8/31,0											45	55	–	56,2	20,0	23,8		+
AP 8/36,4											39	61	–	43,0	28,0	29,0		+
AP 9/6,0																		+
AP 9/55,9													–	39,0	61,0	n. d.		+
AP 9/57,57													–	39,0	61,0	n. d.		+
AP 11/57,9	69	31									43	57	–	46,6	24,6	28,8		
AP 12/55,8													–	47,9	52,1	n. d.		+
AP 12/56,0													–	47,9	52,1	n. d.	+	+
AP 12/57,5	59	41		100									–	47,9	52,1	n. d.		
AP 12/65,2	40	60		100		Tr	Tr						–	29,6	36,8	33,6		+

Q = Quartz, K = Kaolinite, O = Others, I = Illite, F = Feldspar, S = Smectite, ML = Mixed Layer Minerals, C = Chlorite, M = Mica, Tr = Traces

The heavy mineral content was analysed by Dr. Wolfgang SCHNABEL, Geological Survey, Vienna. Additional determinations were made by x-ray diffractometry.

2.3.3 Results

2.3.3.1 X-ray Analysis

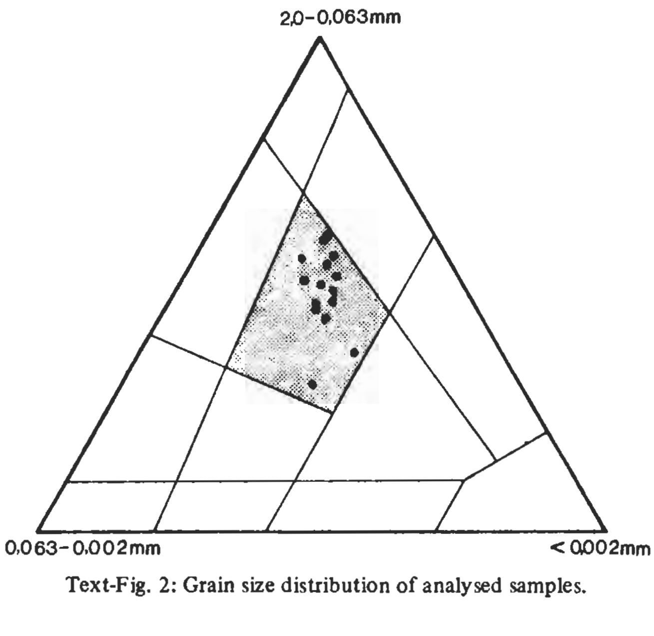
Table 1 shows the results of x-ray analyses as well as the data of other investigations.

The mineral content of all analysed samples is almost identical, except for the samples PU 1 and PU 11; quartz and kaolinite are always the main components, the quartz content varying between 40 and 74 %.

The samples PU 1 and PU 11 contain feldspar as a further primary mineral in addition to quartz. The clay mineral distribution shows kaolinite, illite, smectite, a mixed-layer mineral and traces of chlorite.

2.3.3.2 Grain Size Analysis (Table 1 and Text-Fig. 2)

After determining the grain size distribution, the examined samples were identified as clayey-silty sandstone. The more significant variations were found to occur only in the sand fraction.



Text-Fig. 2: Grain size distribution of analysed samples.

2.3.3.3 Scanning Electron Microscopy

The microfabric as well as the state of development and preservation of the mineral assemblages were examined by SEM.

The smectite minerals determined by x-ray in sample PU 1 could be identified by morphological and chemical investigations, as being fine-textured, rosette-shaped neoformations of a ferruginous smectite – nontronite (Plate 1, Fig. 1–3). It was only in this sample that smectite minerals could be detected, which may be due to a different origin from the other samples.

From the morphological aspect the kaolinite group represents two different types of development. There are winding stacks of pseudohexagonal single plates (Plate 1, Fig. 5, 6; Plate 2, Fig. 1, 2) apart from the heavily encrusted, irregular, single plates of kaolinite in the majority of the samples. Authigenic quartz grains and amorphous coatings in the interstices were also found in these samples (Plate 2, Fig. 4–6; Plate 3, Fig. 1, 2, 4; Plate 4, Fig. 2).

2.3.3.4 Thin Section Analysis

Three fabric types, differing by the matrix/grains ratio could be identified by petrographic thin section analyses. Fabric type 1 is characterized by strongly predominant grains (Plate 5, Fig. 1), in fabric type 2 the grains are distinctly reduced (Plate 5, Fig. 2), whereas they are completely absent in fabric type 3 (Plate 5, Fig. 3).

Numerous rootlet tubes found in the core drilling samples range from Recent formations in the lateritic overburden to fossil remnants in greater depth (Plate 6).

2.3.3.5 Heavy Mineral Analysis

Three different groups of rock samples could be distinguished by heavy mineral analysis. Sample group 1 is characterized by a distinct maximum garnet content, zircon is predominant in sample group 2, whereas garnet is reduced or completely absent. Very small quantities of garnet and zircon were determined in sample group 3. For a better characterization of sample group 3, an x-ray analysis of sample PU 1 was made. The main components are baryte and kyanite.

For further details the reader is referred to the report by AUSTROPLAN 1981 and to former studies cited in chapter 2.3.1.

2.4 Provenance of Pugu Kaolinitic Formation

All authors concerned with the question of the clastic particles' provenance unanimously agree on the crystalline basement complex of the Uluguru Mountains as being the probable hinterland of Pugu Kaolinitic Formation. The complex rock associations of the Uluguru Mountains, including meta-anorthositic rocks of the granulite facies, can be considered as probable source rocks of most mineral grains present in the heavy mineral analysis. Also highly feldspathic rocks are a conspicuous element of these rock associations (SAMPSON & WRIGHT 1964).

In several heavy mineral preparations of the Pugu Kaolinitic Formation and the interlayering "claybound sands", kyanite represents a significant component. In the granulites of the Uluguru Mountains, kyanite is relatively uncommon and appears to be mainly restricted to distinct graphitic rocks, with the mineral assemblage graphite-kyanite-plagioclase-kalifeldspar-quartz and an extremely unusual "garnet-kyanite rock", consisting of rounded garnets, set in a matrix of quartz and kyanite; rutile is an abundant accessory. Modal analyses of garnet-kyanite bearing rocks (kyanite-garnet-biotite schist, kyanite-biotite-garnet gneiss, and others) are provided by SAMPSON & WRIGHT 1964. SAMPSON 1957 reports the occurrence of kyanite-bearing pegmatite. In some of the larger pegmatites considerable amounts of both potassium and sodium feldspars also occur (SAMPSON 1956).

The provenance of baryte in greenish montmorillonitic arkosic sandstones, intercalated between layers of drab kaolinitic sandstone (see Table 1, sample PU 1), is not clear. However, the euhedral shape displayed in the heavy mineral preparations, is conceivably due to their alteration from feldspars (FÜCHTBAUER 1967).

The general geomorphology and in particular the inferred drainage pattern clearly indicate that east of the Uluguru Mountains sediments of the Karroo, marine Jurassic, Cretaceous and Tertiary up to Lower Miocene and superficial deposits should also be included in the drainage basin of a "Pre-Ruvu River".

The Karroo rocks of the Mvuha area, the Mvuha Beds, crop out in the eastern foothills of the Uluguru Mountains. According to SPENCE 1957, they comprise the following mappable units: very coarse conglomerates with some green shales (diamictite); shales and siltstones, partly varved; very coarse sandstones, in part feldspathic and containing small pebbles of quartz and feldspar up to 1 inch in diameter. The conglomerates include glacial outwash gravels. The lithology of the Mvuha Beds suggests that they were deposited in glacial conditions during Dwyka glaciation.

In the upper course of the "Pre-Ruvu River" besides the various rock types of the Uluguru Mountains, feldspathic sediments of the Karroo also contributed as source rocks to the Pugu Kaolinitic Formation. Some of the channel lag deposits, consisting of spheroidal shaped quartz-gravels, probably were mostly derived, at least in part, from Karroo glacial diamictites and conglomeratic beds.

On its easterly course, the river bed of the "Pre-Ruvu" had to pass mid-way an area covered by marine Jurassic and Cretaceous formations. Closer to the former shore of the Indian Ocean, marine sediments of Tertiary age (up to Lower Miocene) also occur in its middle and lower course.

Last but not least, superficial sediments – often kaolinitized – are also likely to have contributed considerably to the stream load. These sediments comprise the kaolinitic "Forest-Cap Clays" (SAMPSON 1956), as well as superficial sandy soils and the various sediments of alluvial origin, such as sands, silts, muds and boulders.

Uplifting and tilting of the Pugu Hills (see chapter "Structural Geology") towards the west after Miocene time caused the termination of active deposition in the delta plain of Pre-Ruvu River. The modern Ruvu River most probably represents a resequent stage of the older river bed in a northeastern direction.

2.5 Sedimentary Environment of Pugu Kaolinitic Formation

2.5.1 Sedimentary Facies

Due to the isolated and highly diverse outcrop situation, the interpretation of the sedimentary environment of Pugu Kaolinitic Formation proves to be a difficult task. Because this question is of eminent importance for the understanding of the deposit's geometry, this paper also attempts to provide a p r e l i m i n a r y interpretation, based on the incomplete data available. The following papers also deal with the sedimentary environment, often with contradicting results: TRUTER 1947, GUEST 1949, HOLROYD 1954, ROBERTSON et al. 1954, McKIE 1955, HOROBIN 1957, BARTHOLOMEW 1963, SOLESBURY 1964, BERNIUS 1967, KENT et al. 1971, and CILEK 1979. The papers by HOLROYD 1954, BERNIUS 1967 and KENT et al. 1971 confirm the present authors ideas, i. e. deposition of Pugu Kaolinitic Formation in fluvial environments respectively under strict freshwater conditions on the upper delta plain.

According to TURNER 1980, delta plains are low-lying areas which in their fluvial domains are cut by active and abandoned fluvial distributary channels and also show a variety of interchannel areas, the socalled interdistributary environments. The Pugu Kaolin Formation also shows typical features of the distributary channel environment, as well as the interchannel areas.

Massive channel-fill sandstones, some more than 12 m thick, with a significant gravel layer of approximately 60 cm thickness, are exposed at the portal to adit D (Plate 8, Fig. 2) in the present kaolin workings and along Central Railway Line. The mineralogy of "Type D" kaolinitic sandstone was described in detail by ROBERTSON et al. 1954. In several of the boreholes, massive channel-fill sandstones with basal or intraformational lags, comprising well rounded gravel of diameters in the range of 4 mm to several centimeters were also encountered. The gravel layers show thicknesses ranging from strings of isolated pebbles up to more than 50 cm and in some places pinch out laterally. The sand grains show poor sorting, the variation of grain sizes can most probably be attributed to constantly changing river courses, the sandy material being transported in the channels in fairly fast flowing muddy water. The coarser sediments have been deposited in the river channels, as documented by "scour and fill" structures, the absence of bedding, and the common occurrence of lag conglomerates. In part, these sediments also can be expected to represent crevasse-splay deposits. The finer-grained sands, silts and clays, however, predominate in the backswamp environments.

The inter-channel areas are composed of kaolinitic clayey-silty sandstone units and more rarely of clay/mud-dominated sandy rocks, often with abundant rootlets and colour mottling. The colour mottling is in most cases due to abandoned root canals, and in addition concentric spheroidal brick red patches, with diameters ranging to more than 20 cm occur. White or drab colouration is predominant. Infrequently there are also interlayers of dark purple clayey red beds and greenish arkose sandstones present, as documented in sample PU 1. A single significant red bed layer at the Mambisi National Housing Estate is used for tiles and in cavity-bricks manufacture. The green "clay bound sands", located 1 km east of the present kaolin plant, are of local economic importance for tile manufacture. From this locality one sample (PU 11) is described mineralogically in Table 1.

The red bed layers – usually having a thickness of the order of 1 m and associated with root scars – closely resemble paleosols, a characteristic feature of red beds formed in delta plain environments (TURNER 1980). The formerly abundant vegetation cover, indicated by rootlets and root scars, could have been responsible for trapping the mud-sediments and for their purple colouration.

An impressive outcrop of drab thin-bedded to laminated fine-grained kaolinitic sediments with occasional sand streaks and containing extensive burrows and roots, is exposed at a narrow curve in roadcuts of the Kisarawe–Kazimzumbwi road. The origin of the burrows is not clear and it seems a strange coincidence that organic activity did not completely destroy the stratification. These types of sediments probably represent a backswamp (lacustrine ?) environment.

Cross-bedded sandy siltstones with fine-grained interlayers, the latter occasionally laminated, crop out at the Central Railway Line, close to the Mambisi National Housing Estate (Plate 8, Fig. 1). With some reservation, these strata can be attributed to deposition on natural levees.

2.5.2 Fossil Roots and Root Moulds

Fossil root burrows are abundant in many parts of Pugu Kaolinitic Formation. Although rather rarely, even dry shrivelled-up root substance is still preserved and can be obtained in very small quantities from the root canals. Root moulds (SARJEANT 1975) are generally preserved as more or less vertical pipes, sometimes branching, with diameters from less than 1 mm up to about 8 mm (Plate 6; Plate 7, Fig. 1). In most cases the hollow cylindrical tubes of the root moulds are coated on their walls by ferruginous matter, with either brickred, purple or rustybrown colour. As a general feature hollow root moulds and rootlets seem to be more frequently preserved in the sandstone member of Pugu Kaolinitic Formation rather than in the finer clastic domains. However, the sandy kaolinitic claystones and mudstones in addition to the preserved features described, show occasionally abundant mottling predominantly of purple, redbrown or rustybrown, more scarcely of mauve or dark violet complexion. Because some of the mottles can be traced into clearly preserved root canals, they may be readily attributed to the action of decaying plant roots.

In the cores of the STAMICO/AUSTROPLAN drilling program, fossil root structures, including shrivelled-up root substances, can be observed downwards to depths of more than 60 meters. Root burrows are not restricted to the white or drab kaolinitic sediments, but can also be observed in red bed intercalations and of course in the lateritic soil cover. An outcrop of a sequence of drab kaolinitic sediments intercalated with a red bed layer occurs along an access road to the STAMICO 1979/80 drilling area, close to the "Testborehole" (Plate 4, Fig. 4). This sequence shows vertical tubular zones of bleaching, due to downward percolating ground water along former rootlet moulds.

In a delta plain environment plants may have grown submerged in marshes, on temporary dried areas of the floodplain or on natural levees marginal to the distributary channels. The scarcity of plant debris in the parts of Pugu Kaolinitic Formation studied can most probably be attributed to rapid decomposition and oxidation prior to burial. The well-drained swamp deposits of the Mississippi delta also contain virtually no organic matter.

Apart from joints and fractures, secondary porosity may be enhanced by root penetration. The downward percolation of descending waters enriched in humic acids along abandoned rootlet tubes, which causes reduction of Fe^{3+} to Fe^{2+}, thus bleaching the surrounding host rock, is well documented in various of the outcrops in the Pugu Hills (see next chapter). The supposition, however, that these descending acidic waters could also be responsible for the alteration of feldspars to kaolinite in the arkosic sandstones could not be either confirmed nor disproved to date by mineralogical investigations. STAUB & COHEN 1978 report on soils penetrated by roots below peat, enriched in kaolinite due to leaching by humic acids percolating downwards. Familiar examples of soil formation – often enriched in kaolinite – due to this mechanism are provided by the seat earths below coal seams in the Upper Paleozoic Coal Measures of the U. S. A. There are, however, no indications of seat earth-horizons anywhere in the Pugu Hills, despite rare lignitic streaks encountered at Pugu No. 2 borehole by BP–SHELL (KENT et al. 1971) in "claybound sand".

2.5.3 Secondary Reduction Zones

An interesting feature, which still requires further research, is the presence of white or drab bleached zones in an otherwise redbrown indurated arkosic sandstone, exposed in a small quarry on the road from Kisarawe to Kazimzumbwi village. As shown in Plate 4, Fig. 3, two types of bleached zones can be observed, i. e. concentric spheroidal shaped and horizontal zones.

The spheroidal zones have generally a dark centre, the leached haloes being arranged more or less concentrically around it. The diameter of these vertical tubular bodies, showing spheroidal cross-sections, range from 10 to 18 cm, the dark, central, irregularly or spherically shaped spots are of the order of 0.5 to 2 cm. The latter can be attributed to root canals, which provided ready access to the percolation of reducing ground water and subsequent bleaching of the neighbour host rock by reduction of Fe^{3+} to Fe^{2+}, with associated dissolution of pigmentary oxides. Petrological investigations show that the macroscopically well defined boundary between the redbrown host rock and the bleached zone cannot be identified by the microscope. On the contrary, the clayey matrix of the white reduction zone shows darker complexion than in the host rock. The dark grains of iron oxides (goethite ?) which cause the redbrown colouration of the host arkose sandstone are, however, practically absent in the leached haloes.

The horizontal bleaching zones are a few centimeters thick and are clearly related to fissures, providing easy access to percolation of waters enriched by humic acids.

It remains an open question, if the bleaching phenomenon by reducing ground waters rich in humic acids is responsible in part or even on a large scale for the white or drab colouration of the Pugu Kaolinitic Formation. We could not find any indications, however, that the bleached haloes at sample point PU 16 show more pronounced kaolinization than the redbrown arkose host rock. (The useful discussions on this topic with Dr. Otmar SCHERMANN, Geological Survey, Vienna, are much appreciated.)

Concerning secondary reduction zones, discussed in detail by TURNER 1980, it should be noted that concentric bleached zones or reduction spots respectively, in comparable rock units in other parts of the world – as in the U. S. A. – contain appreciable concentrations in uranium, vanadium, copper and other minerals of economic interest. Some uranium-bearing sandstones show cross-bedding with conglomeratic erosional bases and typical channel geometrics (SELLEY 1976). Uranium ore bodies can also occur in "roll fronts", especially on their highly altered and bleached concave side, where the matrix and feldspars are extensively kaolinized. By using a scintillation counter a selection of fieldsamples and cores from Pugu Kaolinitic Formation were checked in Vienna for gamma radiation, unfortunately with negative results. However, systematic research has not been focussed so far on this topic.

2.6 Considerations on the Genesis of Pugu Kaolinitic Formation

All authors unanimously agree on the sedimentary origin of Pugu Kaolin Deposit. However, many detailed questions still remain unsolved and the data available are interpreted in different ways. The main questions to be discussed relate to the origin of kaolinite and the time of kaolinization, both of them are intimately connected with the provenance of detritic particles and the depositional environment of the Pugu Kaolinitic Formation.

There are at least three theoretical possibilities for the accumulation of kaolinite in the Pugu Hills. The first one, which is definitely proved by petrological studies is an in situ kaolinization of arkose sandstones and similar associated highly feldspathic fine-grained sedimentary rocks.

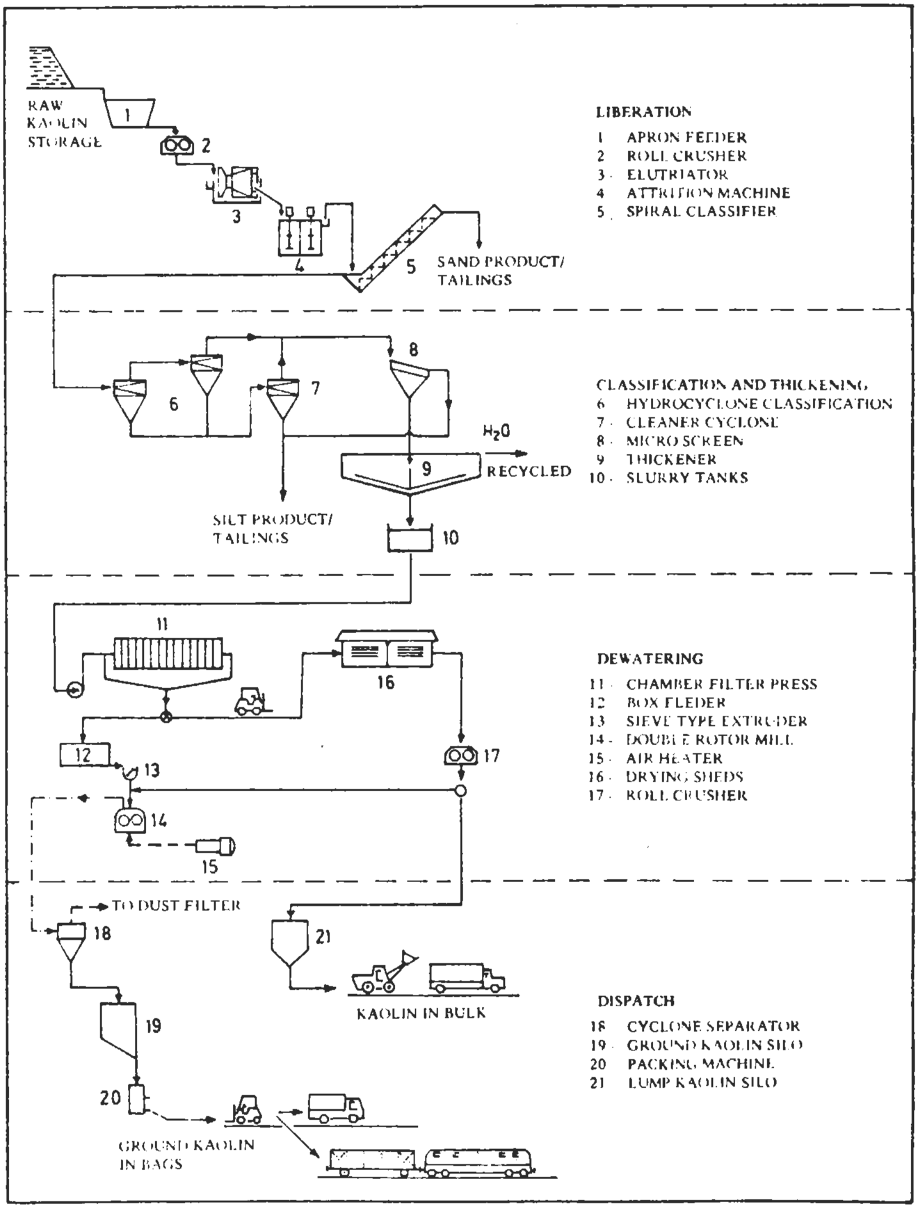
A second source of kaolinite, which could be of eminent importance for the accumulation of "Type D" kaolinitic sandstones, is most probably a kaolinite which was transported from a far source. It could be derived from kaolinitic weathered crusts, e. g. the "Forest-Cap Clays" of the Uluguru Mountains and from other kaolinitic residual sediments, as mentioned in chapter 2.4. The mechanism of sedimentation of "Type D" kaolin favoured by the present authors is a fast long-distance transport in muddy waters of the "Pre-Ruvu River", followed by deposition in the low-energy areas of the river or its distributary channels in the flat upper deltaic plain. Alternatively, it cannot be excluded, that the extensive sand filling of channels is a result of pronounced bi-directional bed shear in an inner tidal delta. The smectite-bearing sandstone of sample locality PU 1 and similar occurrences, may also indicate a marine influence (ROBERTSON et al. 1954, CILEK 1979).

As a third possible source of kaolinite, postdepositional reworking and subsequent redeposition of already more or less consolidated kaolinitic rocks within the Pugu Kaolinitic Belt should be considered. Actually, there also appears some proof for this kind of genesis for part of the sediments. This is indicated by accumulations of coarse-grained sediment clasts in "scour and fill" structures. As can be seen in the exposure displayed in Plate 7, Fig. 2 part of the redeposited material consists of sharp-edged flakes and chips of kaolinitic sediments, eroded from the immediately underlaying bed into which the mini-channel cuts. The eroded and redeposited coarse-grained clasts show sharp boundaries against the surrounding matrix. This feature – with some reservation – provides evidence for an early stage of kaolinization, probably starting contemporaneously with the exposition of sediments to weathering agents. It is to be expected, that such relatively delicate structures as clast boundaries within a lithologically uniform bed would have been completely destroyed during a late diagenetic alteration of a feldspathic parent rock.

As a result of quick facies changes, the presence of current bedding and channel structures, together with beds and lenses of green and red clays, CILEK 1979, argues against the idea of kaolinization in situ during the Lower and Middle Miocene. Without doubt, further investigations are still necessary to enlighten this complex subject.

According to PATTERSON & MURRAY 1975, the deposits whose origins are least understood include those in the extensive kaolin belt in Georgia and South Carolina, U. S. A.

This statement is truer still by far for the Pugu Kaolin Belt. Nevertheless, in consulting the literature on the U. S. deposits (VEATCH 1908, 1909, NEUMANN 1927, KESLER 1956, PATTERSON & MURRAY 1975), many similarities with the kaolin occurrences in the Pugu Hills are evident. Regarding the provenance of U. S. kaolinitic material, a strongly weathered Piedmont surface was assumed to represent the hinterland; the kaolin being transported by streams to the area of deposition. The mineralogical analysis of the kaolinites also shows in part accordion-like booklets, proving in situ genesis of part of the kaolins, probably due to postdepositional alteration of highly feldspathic sediments. There is no agreement, if the kaolins were either formed under freshwater conditions, or in littoral respectively deltaic environments under marine influence. A striking similarity to the Pugu kaolin deposit is a lens-shaped occurrence of kaolinitic raw material and the highly unsorted nature of the sand frac-



Text-Fig. 3: Simplified Process Flow-Sheet tion. Smectite is also present in some deposits in varying quantities. ROBERTSON et al. 1954 even compare the similar crystal forms of Georgia and Pugu euhedral kaolinites. In our opinion a comparison between the U. S. and Pugu kaolin belts, comprising field data and detailed mineralogical investigations, could provide supplementary information for a better understanding of the genesis of both these kaolin belts.

3. Mining and Processing Aspects

Up to 1981, STAMICO extracted kaolin from a small underground mine with a production capacity of less than 10 000 tons/year, employing a modified room and pillar method. At that time, an analysis of the projected future domestic demand in Tanzania, and the identification of a limited, yet notable export potential for kaolin products clearly established that present mine capacity should be increased substantially within the next years to some 110 000 tons/year run-of-mine kaolin.

In view of the fact that, within the target area selected, kaolin occurs in the form of a near-surface deposit with overburden thickness in the range of 10 to 18 m and a strip ratio of less than 1 : 1, surface mining should be considered as the optimum mode of operation. However, due to the high degree of lateral and vertical quality variation of the raw material, selective mining combined with continuous quality control should be applied. This would be greatly facilitated if an adequate number of extraction points with different quality characteristics were exposed, where good quality and poor quality material are mined and loaded in such proportions that the total blend will possess the desired properties. Thus, under the conditions prevailing in the target area, multiple-bench mining with low bench heights should be regarded the appropriate method, providing the flexibility required for selective mining.

A comprehensive laboratory and semi-industrial test program, conducted on the subject raw material, confirmed that products for a variety of industrial applications can be obtained. Processed Pugu kaolins possess favourable ceramic-properties and are well suited as carrier-substances in pesticides and as fillers in rubber, paint, and bitumen. A good filler-grade kaolin can be produced by increasing the proportion of the higher-quality component in the mill feed. While it would also be basically possible to produce coating clay from the high-quality portions of the deposit, this would require additional, costly processing steps and would furthermore be associated with a substantial reduction in the recovery rate.

Standard kaolin products can be obtained from Pugu kaolin using a largely conventional flow-sheet, as illustrated in the Text-Fig. 3. The proposed combination of open-air drying in sheds and thermal drying is a good example of an appropriate technology that already has a proven production history. Depending upon the type of raw kaolin processed and the product quality desired, the recovery rate will vary around an average value of about 30 %. In principle, the correspondingly large quantities of quartz sand discharched as tailings could also find several commercial uses with only minor additional processing required. Potential fields of application include building materials, glass and foundry sands, as well as abrasives in sand blasting and as cleansing agents.

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Plate 1

Fig. 1–3: PU 1 – fine textured, rosette-shaped smectite aggregates in micro-cracks and interstices; average diameter of the intergrowths 3,5 μ; the single minerals are shaped as plates with irregular edges; EDAX-analyses indicate ferruginous smectite – nontronite.

Fig. 4: PU 1 – slightly bent mica plate with dissolved structures at the edges.

Fig. 5: PU 16 – irregular stacks of kaolinite; lath-like clay mineral aggregates towards the mineral edges.

Fig. 6: PU 24 – stacks of kaolinite with idiomorphic pseudohexagonal crystals.

Plate 1

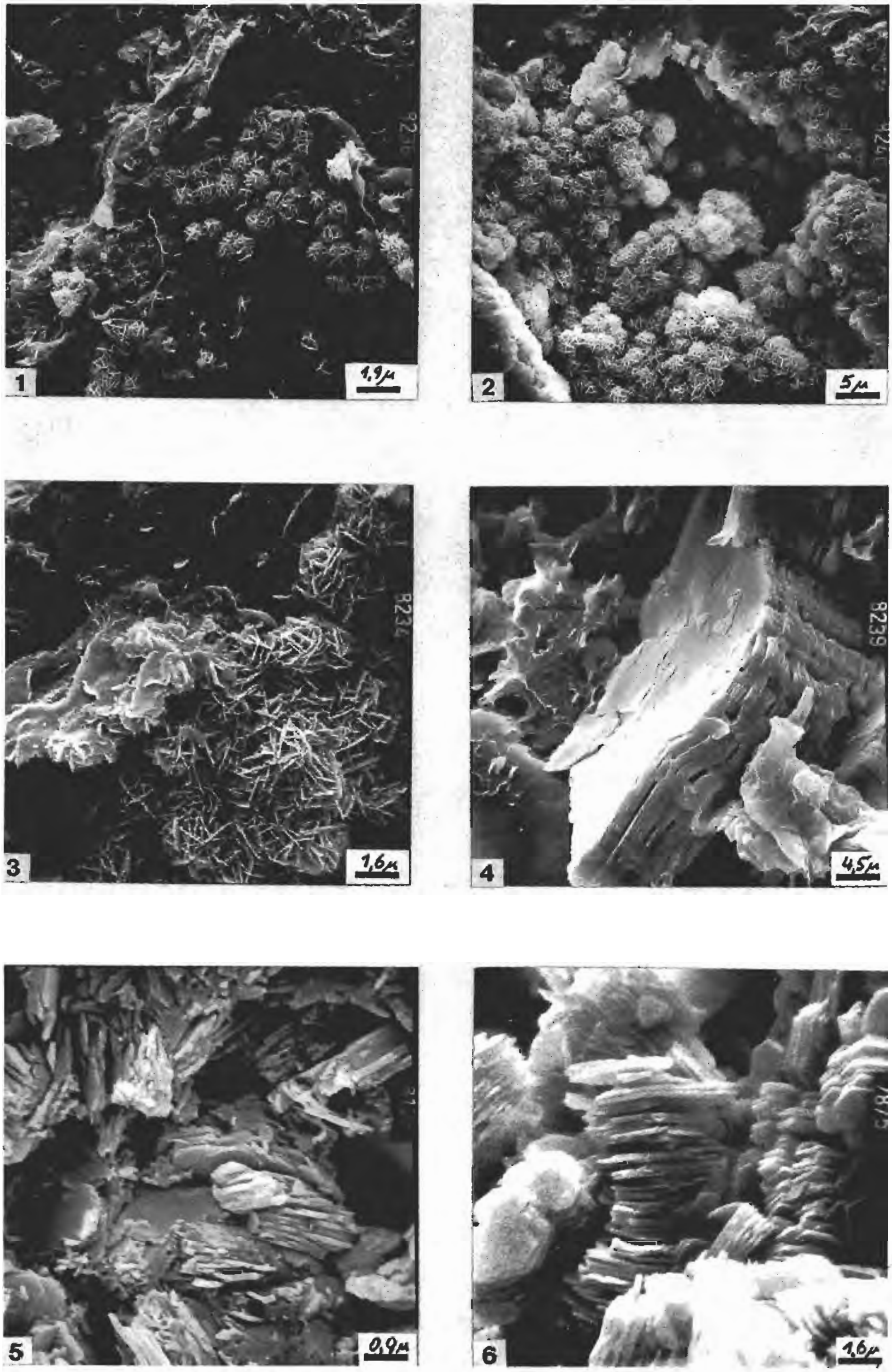


Plate 2

Fig. 1, 2: AP 1/55,2 – vermicular kaolinite aggregates with idiomorphic pseudohexagonal single plates.

Fig. 3: AP 3/8,21 – strong incrustation around smaller and bigger quartz grains.

Fig. 4: AP 3/24,75 – fine-grained porous matrix of Al- and Si-oxides with idiomorphic authigenic quartz.

Fig. 5: AP 3/24,75 – detail of Fig. 4 with authigenic quartz.

Fig. 6: AP 6/26,5 – loose, cavernous fabric with numerous quartz grains.

Plate 2

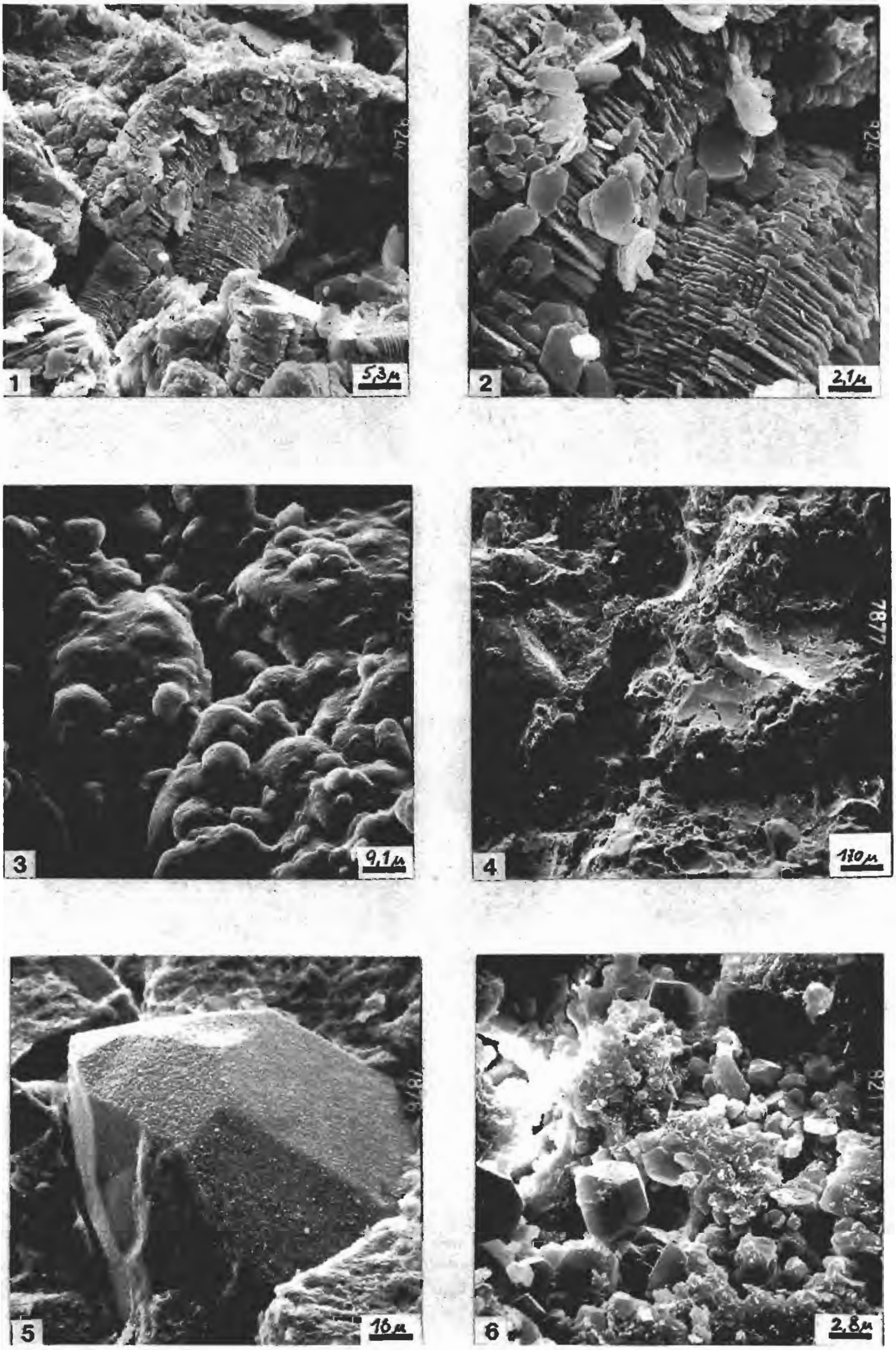


Plate 3

Fig. 1: AP 6/51,25 – concentration of authigenic quartz grains.

Fig. 2: AP 7/26,8 – interstices with amorphous SiO_2-coatings.

Fig. 3: AP 7/26,8 – a higher magnification reveals a resolution of the coating in single aggregates.

Fig. 4: AP 7/26,8 – idiomorphic quartz grains in a matrix with coated kaolinite aggregates.

Fig. 5: AP 7/37 – matrix with irregularly shaped and loosely arranged kaolinite plates.

Fig. 6: AP 7/48 – ball- or kidney-shaped Fe-rich concentration in dark violet rootlet tubes.

Plate 3

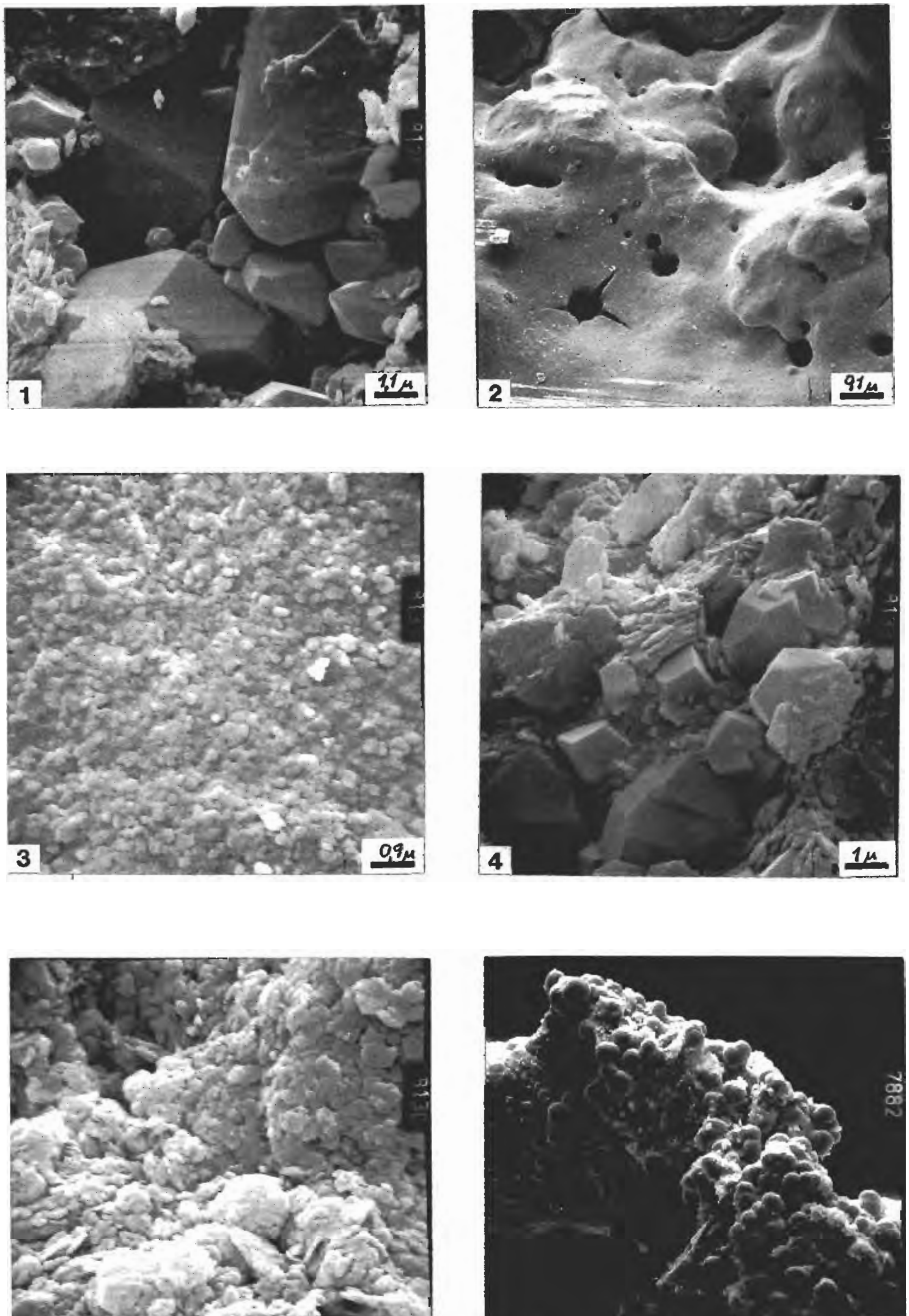


Plate 4

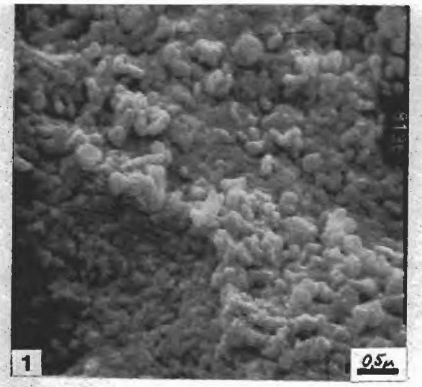
Fig. 1: AP 12/56 – a fine-grained clay mineral matrix with poorly crystallized Fe-oxides in rootlet tubes.

Fig. 2: AP 12/56 – Fe-rich matrix with authigenic quartz crystals.

Fig. 3: Sample point PU 16. – Road from Kisarawe to Kazimzumbwi village, north of Zumbwi river bridge. – Arkose sandstone with zones of bleaching due to secondary reduction of Fe^{3+} to Fe^{2+}. Note two types of bleached zones, namely spheroidal haloes with dark centres originating from root penetration and horizontal zones along fissures.

Fig. 4: Acces-road to "Testborehole" in STAMICO 1979/80 core drilling area. Vertical bleaching zones caused by downwards percolation of acid waters along intact and abandoned root canals in the hanging part of a kaolinitic sandstone/red bed-sequence.

Plate 4



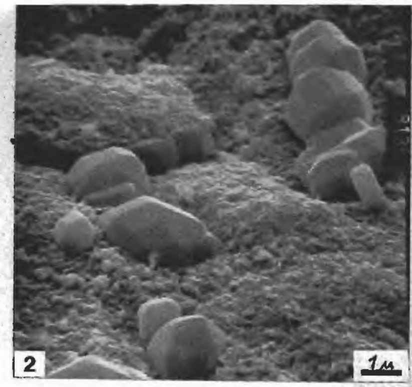


Plate 5

Fig. 1: AP 12/55,8 — the fabric is characterized by grains strongly predominating the matrix, which is infiltrated with opaque to reddish-brown transparent Fe-oxides. The grains are rounded and angular quartz with mostly straight extinction and various grain size.

Fig. 2: AP 2/50,2 — bigger, corroded quartz grains are distinctly reduced in relation to the predominant Fe-rich clayey matrix.

Fig. 3: AP 9/57,57 — the partly colourless or light-brown mainly clayey matrix consists of sericites and small, corroded quartz grains; no coarser quartz grains.

Fig. 4: PU 16 — numerous vermicular clay mineral aggregates (kaolinite) in a matrix strongly infiltrated with Fe-oxides.

Fig. 5: PU 16 — distinct dissolution structures corresponding to the zoning in bigger plagioclase grains (ϕ up to 0,8 mm).

Fig. 6: AP 4/24,5 — in the thin section the macroscopic violet zones show a fine-grained assemblage of reddish Fe-oxide particles; the subrounded to angular quartz grains are mostly fractured.

Plate 5

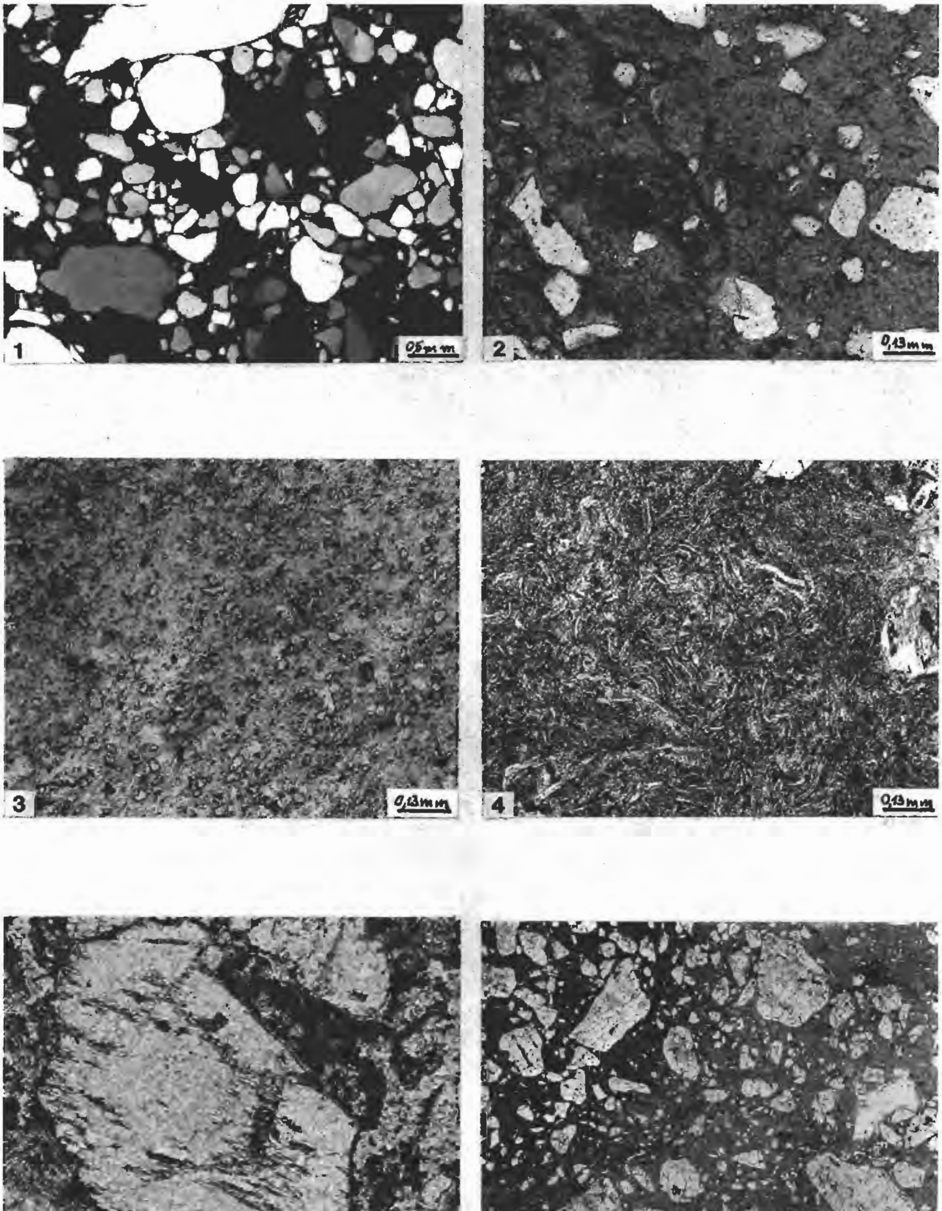


Plate 6

Fig. 1: AP 9/6 – Lateritic overburden; mainly angular quartz grains in a light-brown, very dense matrix; opaque Fe-oxide concentrations especially in rootlet tubes (centre).

Fig. 2–4: AP 9/57,57; AP 4/9,05; AP 12/56 – Fe-oxide concentrations in the rootlet tubes, in the centre zones with birefringence; opaque formations on the edges change into single grains in the matrix.

Fig. 5: AP12/65,2 – striking concentrations of relatively fresh quartz grains with slightly undulous extinction in cracks and rootlet tubes.

Fig. 6: AP 12/55,8 – the central zones of distinct rootlet tubes show a removal of Fe-oxides, as a result of reducing conditions.

Plate 6

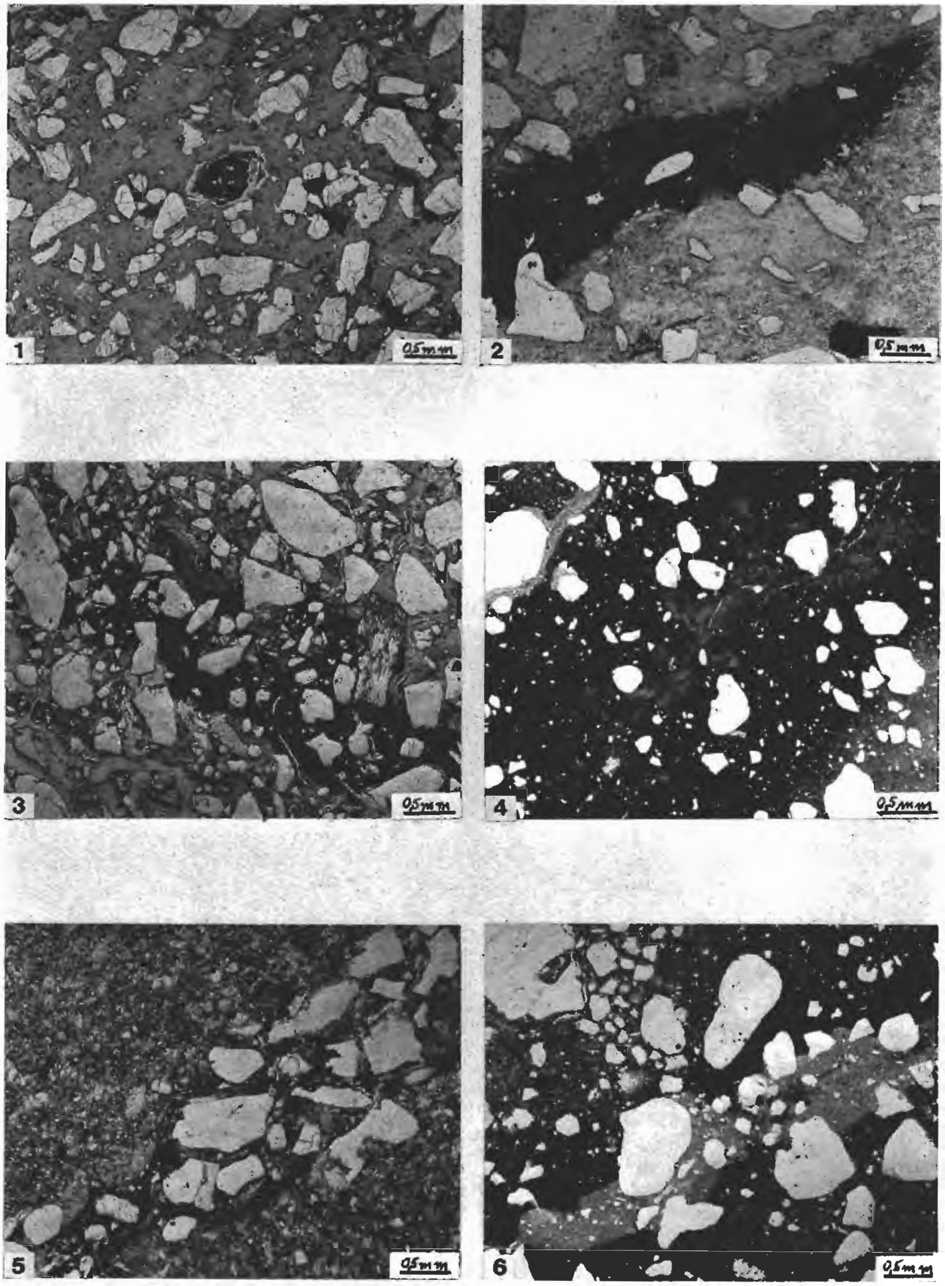


Plate 7

Fig. 1: Core of kaolinitic sandstone with fossil root moulds. STAMICO/AUSTRO-PLAN-drillhole AP 8/17,8 m; approximately natural size.

Fig. 2: Central Railway Line, close to Mambisi National Housing Estate. "Scour and fill"-structure and burrowing in fine-grained kaolinitic sediments.

Plate 7

2

1

Plate 8

Fig. 1: Crossbedding and burrowing in fine-grained kaolinitic sediments; location as Plate 7, Fig. 2.

Fig. 2: West of entrance to adit D, at present Pugu kaolin plant. "Type D" kaolinitic sandstone with prominent conglomeratic pebble layer; probably fluvial channel lag deposition.

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