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SCANNING ELECTRON MICROSCOPE STUDY OF BAUXITES OF DIFFERENT AGES AND ORIGINS

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Abstract—Sixty-five bauxite samples of different ages and origins were studied by scanning electron microscopy. Only broken surfaces of the specimens were investigated. Size and form of individual crystals and of grain aggregates were studied as were different types of microtextures and space-fillers.

Grain size varies from 0.05 μm to 1 mm. Smallest is the grain size of young karstic bauxite deposits that is explained by a physicochemical retardation effect of the carbonate environment. Significant differences were found by comparing the space-filling of karstic and lateritic bauxite deposits. High-level and low-level lateritic deposits show differences as well.

A combined use of macroscopic observations, petrographic microscopy, electron microprobe, SEM, and TEM furnishes the best clues for any genetic interpretation of bauxites. SEM studies are useful in solving technological problems of bauxite processing.

Key Words—Bauxite, Boehmite, Diaspore, Gibbsite, Halloysite, Karstic, Laterite.

INTRODUCTION

Studies of claylike rocks have been made during the last few years by a growing number of SEM investigators (Bohor, Hughes 1971). The most important work in this field was done by Keller (1976, 1977) who published papers in *Clays and Clay Minerals* on the SEM investigation of kaolins from diverse environments of origin. The outstanding results of these papers inspired us to undertake a similar study on bauxites. Additional encouragement for this work was a visit in 1976 by Professor Keller to Budapest and to some major bauxite deposits of Hungary.

The first SEMs of bauxites were published by Lahodny-Sarc et al. (1972). They found significant differences between micrographs of karstic and lateritic bauxites by comparing two bauxite samples from Yugoslavia and one from Sierra Leone, respectively. Caillère and Pobeguin (1973) published SEMs of diaspore crystals from a bauxite sample of Ariège, France. Bushinsky (1975) published a SEM of diaspore crystals with hematite from a bauxite sample from the North Ural Mts. Zámbo and Solymár (1973) compared the technological properties of a Hungarian bauxite using its SEMs. In continuing this work Solymár (1975) compared four Hungarian and three Soviet bauxite samples, and found a close relationship between their SEMs and some of their technological parameters.

All of this work dealt with a small number of bauxite samples. The aim of our present work is to give a more comprehensive evaluation based on a greater number of samples representing bauxite deposits of different ages and origins from all over the world.

METHOD OF INVESTIGATION

Our investigations were carried out on a JSM–U3 type JEOL scanning electron microscope. Generally 25-kV accelerating voltage and 10-picoampere current intensity were used, but in some cases we lowered the current intensity to achieve a better resolution.

Only broken surfaces of the specimens were investigated. We found, in good accordance with Keller (1976), that grinding of the specimen introduces an artifact and thus leads to erroneous interpretations. The surface of the samples was covered by an ~20-μm graphite and a 15-μm gold layer using a vacuum evaporator.

The samples were studied first at low magnification to observe their overall characteristics. As a next step, micrographs were made on selected points of the sample with magnification increasing up to 30,000×, and in some cases to 60,000×. All micrographs were taken with the secondary electron mode.

Sixty-five samples from our collections were studied. Their location is shown in Figure 1. We summarized their geologic, mineralogic, and petrographic data in Table 1. The mineralogic composition of each sample was determined by X-ray powder diffraction, thermogravimetry, and infrared methods. Forty-six samples are from karstic, 18 from lateritic and one from the tichvin-type bauxite deposits. In the table the karstic bauxites are arranged by age; the lateritic ones by geographic location.

The following features were studied by SEM on all samples: size and form of individual crystal grains or (crystallites); morphology of the grain surface; size and form of grain aggregates (lumps, and/or stacks); size and configuration of microcavities within the sample; interrelation of grains, aggregates, and cavities or "space-filling"; and from knowledge of the bulk mineralogical composition of the samples and using an EDAX 711 X-ray analyzer we tried to identify the crystals shown in SEM.

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Table 1. Main geologic and mineralogic data of the samples investigated by SEM.

Locality, Country	Age	Mineralogic composition (in diminishing order)	Macro-texture	Overburden meter	Tectonic effects
Karstic bauxites					
Maré Island, Loyauté Islands	subrecent	am,gi,g,cr,b,an	pelitomorph	–	–
Samar Island, Philippine Island	Pleist.	gi,b,g,cr,an	pelitomorph	–	–
South Manchester 2, Jamaica	U. Mioc.	gi,h,g,an,b,k,r	pelitomorph	–	–
South Manchester 3, Jamaica	U. Mioc.	gi,h,b,g,an,k,r	pelitomorph	–	–
South Manchester 4, Jamaica	U. Mioc.	gi,h,g,k,an,b,r	pelitomorph	–	–
South Manchester 5, Jamaica	U. Mioc.	gi,h,g,an,b,k,r	pelitomorph	–	–
South Manchester 6, Jamaica	U. Mioc.	gi,h,g,k,an,b,r	pelitomorph	–	–
South Manchester 9, Jamaica	U. Mioc.	gi,h,g,k,b,an,r	pelitomorph	–	–
South Manchester 10, Jamaica	U. Mioc.	gi,h,g,k,an,b,r	pelitomorph	–	–
South Manchester 11, Jamaica	U. Mioc.	gi,h,g,an,mh,b,r	pelitomorph	–	–
South Manchester 12, Jamaica	U. Mioc.	gi,h,k,g,an,l,r	pelitomorph	–	–
South Manchester 14, Jamaica	U. Mioc.	gi,h,b,g,k,an,r	pelitomorph	–	–
South Manchester 17, Jamaica	U. Mioc.	gi,h,k,g,b,an,r	pelitomorph	–	–
Williamsfield mine, Jamaica	U. Mioc.	gi,h,g,k,an,b,r	pelitomorph	–	–
Rochelois Plateau, Haiti	U. Mioc.	gi,h,b,k,g,an,r	pelitomorph	–	–
Gánt, Ujfeltárás mine, Hungary	M. Eocene	k,b,ch,si,g,h,an,r	microdetr.	10–80	weak
Kincses II mine, Hungary	L. Eocene	b,gi,k,p,an,r	microdetr.	20–100	weak
Kincses II mine, Hungary	L. Eocene	gi,b,h,k,g,an,r	microdetr.	20–100	weak
Iharkút I mine 1., Hungary	Paleocene	k,g,h,an,gi,r	pelitomorph	1–20	weak
Iharkút I mine 5., Hungary	Paleocene	gi,b,h,an,k,r	roundgrain	1–20	weak
Kislőd mine, Hungary	Paleocene	b,h,k,gi,an,r	pelitomorph	10–60	weak
Malomvölgy XI/A mine, Hungary	Paleocene	gi,h,g,k,b,an,r	pelitomorph	5–40	weak
Nyirád, Deáki psz. XVII, Hungary	Paleocene	b,h,k,g,an,r	microdetr.	10–80	weak
Halimba III mine, Hungary	Senonian	b,h,g,do,k,an,r	arenitic	100–300	weak
Bédarieux, Uston mine, France	Senonian	b,k,h,g,an,ru	microdetr.	5–40	weak
Grebnicka Planina, Yugoslavia	Senonian	di,h,b,g,k,r	arenitic	10–100	strong
Spinazzola mine, Italy	Tur.-Cen.	k,b,h,an,g,r	roundgrain	5–40	weak
Brignoles, Mazaugues, France	Tur.-Cen.	b,h,k,an,r	pelitomorph	10–80	strong
Campo Felice mine, Italy	Cen.	b,k,h,an,r	microdetr.	5–80	strong
West-Turgai region, USSR	Cen.	gi,k,h,g,an,r	collomorph	20–60	very weak
Behbahan, Zagros Mts, Iran	Turonian	b,k,h,di,an,r	oolitic	5–150	strong
Megara mine, Greece	Albian	b,h,k,an,di,r	roundgrain	5–100	strong
Padurea Craiului, Rumania	Neocom.	di,b,cm,k,h,an,r	oolitic	10–100	medium
Nagyharsány mine, Hungary	Hauteriv.	di,b,h,k,an,r	oolitic	5–50	medium
Chalkidiké peninsula, Greece	Kimmer.	cm,di,se,ch,r,co	microgran.	5–100	strong + med.
Chalkidiké peninsula, Greece	Kimmer.	di,cm,ch,r,co,an	microgran.	5–100	strong + med.
Zarzadilla de Totana, Spain	Dogger	b,k,gi,h,an,r	arenitic	0–100	medium
Gornje Polje, Yugoslavia	M. Triassic	b,k,h,an,gi,r	pisolitic	5–50	strong
Podlipa, Slovenia, Yugoslavia	M. Triassic	b,h,k,di,an,r	oolitic	10–100	medium
Cao-Bang, Tap-Na, Vietnam	U. Permian	di,cm,k,im,co,r	granular	5–200	very strong
Cao-Bang, Tap-Na, Vietnam	Neogene	di,cd,gi,h,r,cm	granular	–	very strong
Gun, Honan province, China	M. Carb.	di,mu,k,ch,co,an	microdetr.	20–200	weak
Owensville, Missouri, USA	M. Carb.	di,h,k,an,r	microgran.	5–50	–
Brandhurst, Missouri, USA	M. Carb.	di,k,an,ru,h	microgran.	5–50	–
Tyman, Mts, USSR	L. Carb.	gi,b,h,k,g,an	arenitic	80–300	weak
North-Ural Mts, USSR	M. Devonian	di,b,h,k,an,r	arenitic	100–500	strong
Tichvin-type bauxites					
Tichvin, Sinionskoe mine, USSR	L. Carb.	k,g,h,an,gi,r	arenitic	5–80	–
Lateritic bauxites					
Pocos de Caldas, Brazil	high-level	gi,g,k,il,h,an,b,r	relict	–	–
Devona, S. do Mantiqueira, Brazil	high-level	gi,g,k,h,an,b,ru	relict	–	–
Valparaiso, Mantiqueira, Brazil	high-level	gi,g,k,h,an,b,r	relict	–	–
Kassa Island, Guinean Republic	low-level	gi,ma,g,u,an	relict	–	–
Fria mine, Guinean Republic	high-level	gi,pl,k,r,g,an	relict	–	–
Sangaredi mine, Guinean Republic	high-level	gi,k,an,g,r	collomorph.	–	–
Bamako E., Mali	high-level	gi,h,g,k,an,r	macro-piso.	–	–
Bamako F., Mali	high-level	gi,h,g,k,an,r	macro-piso.	–	–
Kibi, Ghana	high-level	gi,g,b,k,h,an,r	collomorph.	–	–
Nyinahin 9, Ghana	high-level	gi,b,h,g,an,r	collomorph.	–	–
Nyinahin 43, Ghana	high-level	gi,h,g,b,k,an,r	collomorph.	–	–
Nyinahin 48, Ghana	high-level	gi,h,g,k,b,an,r	collomorph.	–	–
Saran, Gujarat, India	low-level	gi,di,b,ca,an,k,r	pisolitic	0–10	–
Nandra, Gujarat, India	low-level	gi,k,an,ca,h,di	collomorph.	0–10	–
Dhangarwadi, Maharashtra, India	high-level	gi,g,h,k,an,r	collomorph.	–	–
Pottangi, Orissa, India	high-level	gi,g,h,b,k,sl,r	relict	–	–
Panchpatmali, Orissa, India	high-level	gi,h,g,an,k,b,r	relict	–	–
Weipa, Queensland, Australia	low-level	gi,b,h,k,an,r	pisolitic	–	–

Abbreviations of mineral names: am = amorphous; an = anatase; ca = calcite; cd = chloritoide; ch = chlorite; cm = chamosite; co = corundum; cr = crandallite; di = diaspore; do = dolomite; gi = gibbsite; g = goethite; h = hematite; il = illite; im = ilmenite; k = kaolinite; l = lithiophorite; ma = maghemite; mh = metahalloysite; mu = muscovite; p = pyrite; pl = pyrophyllite; qu = quartz; r = rutile; se = sericite; si = siderite; sl = sillimanite; u = ulvite.

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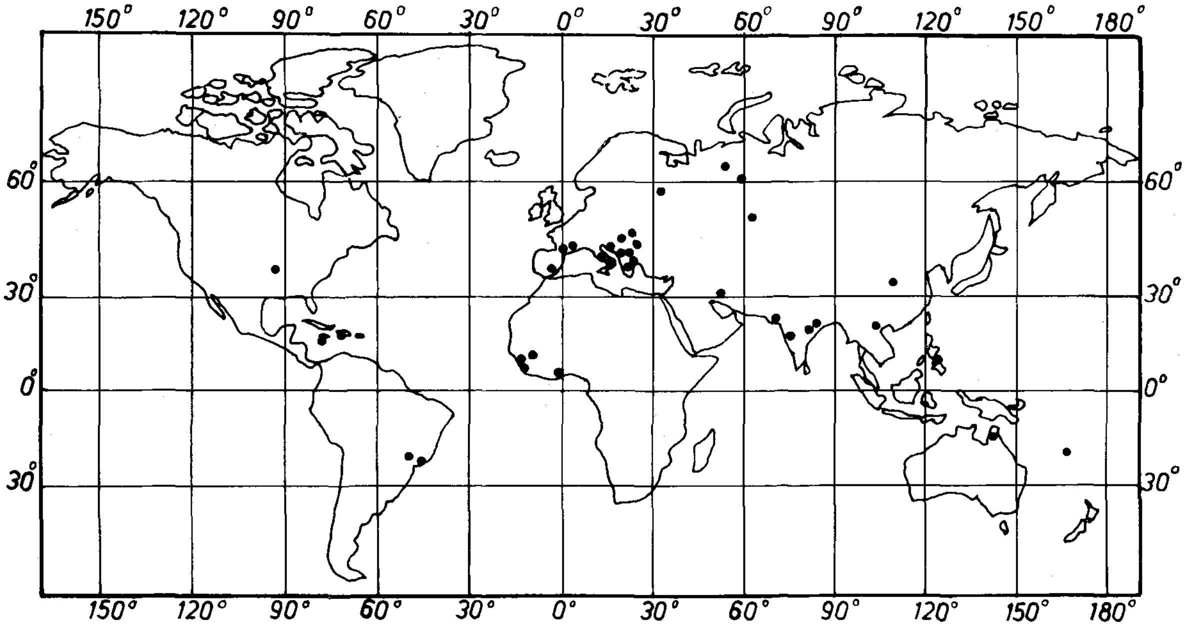

Fig. 1. Location of the bauxite deposits investigated by SEM in this study.

KARSTIC BAUXITES

The grain size and crystallinity of most karstic bauxites increases with increasing age, load of overburden, and tectonic stress. Their porosity diminishes in the same order. We tried to follow this sequence in the description of the SEMs.

The smallest grain size of all investigated bauxites was found in the sample of present-day bauxitization from Maré Island, where it varies from 0.05 to 0.20 μm, most frequently 0.15 μm. The grains are equidimensional and have an irregular flaky shape. They form stacks 20–300 μm in size. These stacks are very loosely packed but are connected, in some occurrences, to yield pillarlike aggregates (Figure 2). This texture develops 60–70% porosity. According to our mineralogical studies of all known bauxites, this kind contains the largest amount of amorphous material. Very probably it contributed to the formation of this very loose or "open texture" (expression of Keller, 1976) as a result of leaching in a limestone environment.

The bauxite of Samar Island (courtesy of G. de Weisse, 1976) is considered to be slightly older than the Maré bauxite. Its grain size varies from 0.05 to 0.4 μm, with the modal size being 0.2 μm. The grains have an irregular flaky shape and are packed into stacks. The stacks are smaller than those of Maré bauxite and do not exhibit columnar forms (Figure 3). At some places, peculiar cellular configurations can be seen when using high magnification (Figure 4). In our opinion, these are the most advanced gibbsite crystallization within the sample.

We investigated 12 Jamaican bauxite samples, all collected from the Manchester plateau deposits: (courtesy of the Jamaica Bauxite Institute). The numbered ones were collected from boreholes whereas the Williamsfield sample came from an open-pit mine. They have a very high porosity (40–50%), and a very similar mineralogic composition (see Table 1). According to our SEM investigation their grain size is also similar, varying between 0.05 and 0.5 μm. The most frequent grain size is generally 0.2 μm. The grains have an equidimensional, irregular flaky shape and form aggregates of 2 to 25 μm. Among the aggregates there are relatively larger open cavities (Figure 5), which is the reason for the high porosity (40–50%) of Jamaican bauxites.

In some places the aggregates are more densely packed and their bulk porosity is also smaller (Figure 6). These samples were collected from large, flat depressions in the Manchester plateau, which are covered by water during the rainy season. In our opinion this environment caused the compaction of the bauxite. Their grain size is slightly larger than that of the others, which we attribute also to the repeated inundation. The sample from the Rochelois plateau, Haiti has essentially the same grain size, microtexture, and space-filling.

All of the above described bauxites come from surface deposits that were never covered by other sediments and were not affected by tectonic pressure. This is the reason for their high porosity and for their very loose stacking and space-filling as observed by SEM.

The bauxites of the Trans Danubuan Mts., Hungary,

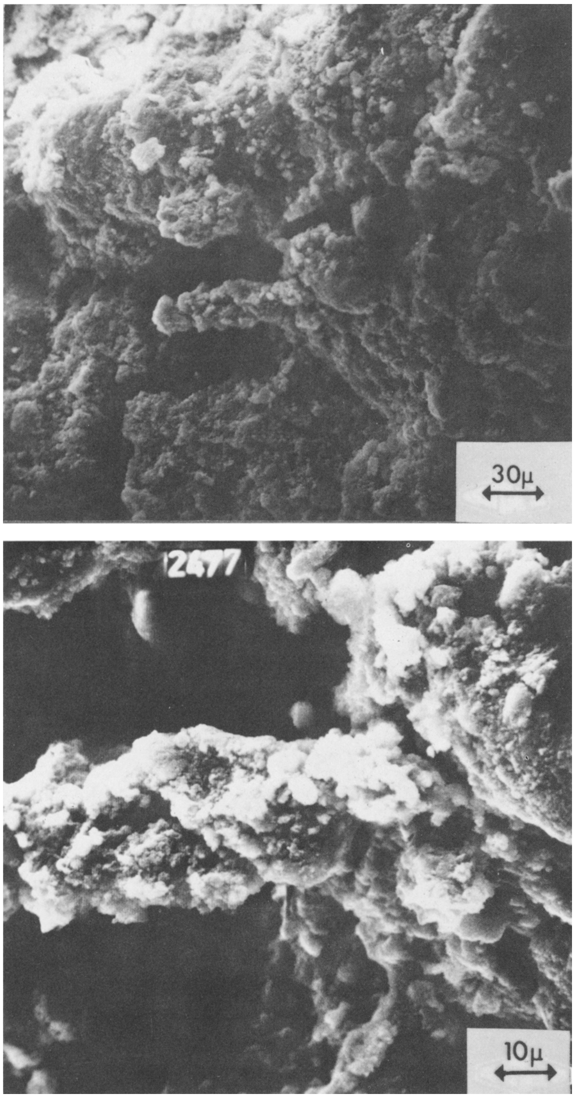

Fig. 2. Subrecent karstic bauxite, Maré-Island, Loyauté Islands. A: 300×; B: 1000×.

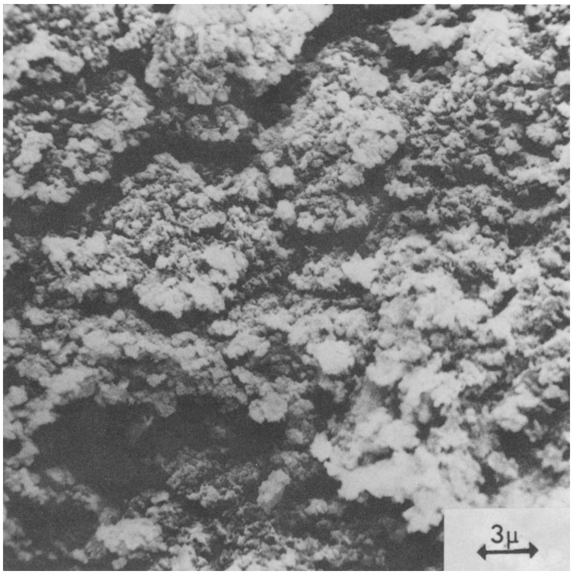

Fig. 3. Pleistocene karstic bauxite, Samar-Island, Philippine Islands. 3000×.

are mainly of Paleocene to middle Eocene age and have an overburden of 10 to 100 m. Only the Senonian bauxites of the Halimba basin are covered by 100 to 300 m of sedimentary rocks. The bauxites have a mixed boehmitic-gibbsitic composition. Only weak tectonic events have occurred in this territory since the bauxites were formed. Therefore, their original stacking and microtexture, as observed by SEM, is preserved although the aggregates are more compacted, and the cavities between them are smaller than those in the bauxites of the foregoing group. The porosity of these bauxites varies from 15 to 30%. The most frequent grain size is 0.1 to 0.3 μm. Only minerals of secondary origin have larger sizes than 5 μm. These values were established by grain-size measurements made with a transmission electron microscope. It is significant that the Halimba bauxites have essentially the same grain size and space-filling as the bauxites of the other deposits of Hungary despite their thicker overburden. This means that the load pressure of a 100- to 300-m thickness of overburden is not sufficient to change the grain size, compaction, and space-filling of the bauxite if there is no additional tectonic pressure.

The Hungarian bauxites are generally equidimensional in grain size, and also have an irregular flaky

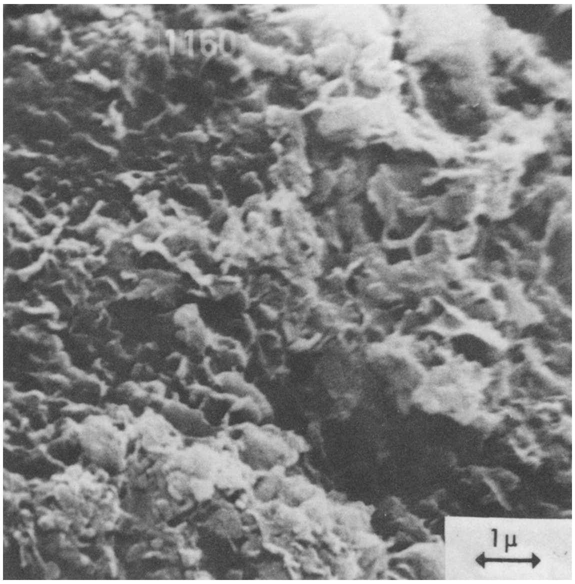

Fig. 4. Pleistocene karstic bauxite, Samar-Island, Philippine Islands. 3000×.

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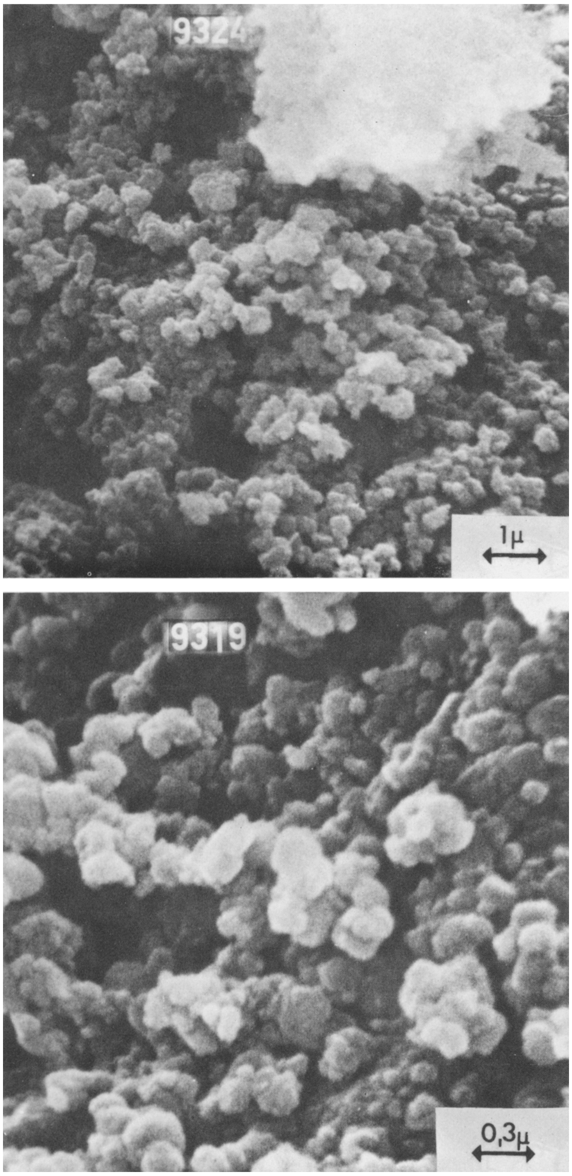

Fig. 5. Miocene karstic bauxite, No. 2., South Manchester plateau, Jamaica. A: 10,000×; B: 30,000×.

shape. In some places small imperfect crystal faces also can be observed (Figure 7). The clayey bauxites and bauxitic clays have a smaller porosity than the low-silica bauxites. Their grain size is the same, but the aggregates are larger and more compacted (Figure 8). In a Cserszegtomaj "flint-clay" (more exactly bauxitic clay) and in a bauxitic clay from Iharkut, a microtexture similar to that described by Keller (1976) for the Missouri flint clays and diaspore clays was observed. Small kaolinite sheaves are interspersed in an irregular, partly swirly pattern (Figure 9). Some larger kaolinite aggregates of 1 to 3 μm also occur.

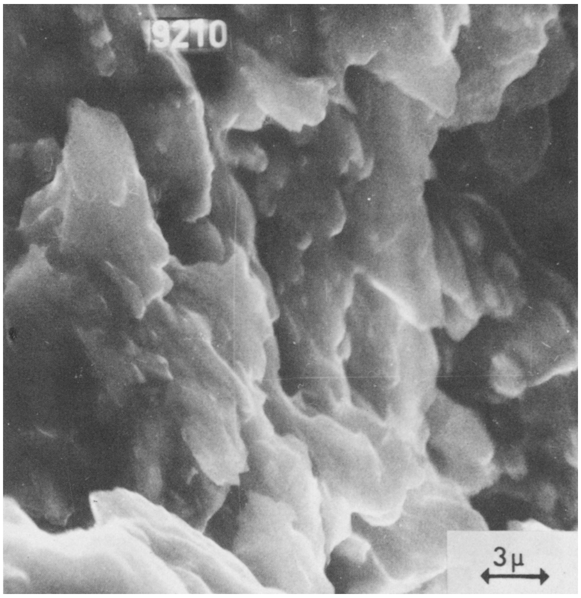

Fig. 6. Miocene karstic bauxite, No. 11., South Manchester plateau, Jamaica. 3000×.

The upper Cretaceous bauxite deposits of Spinazzola, Italy, and Bedarieux, France, are characterized by similar weak tectonic activity following bauxite formation. They have a boehmitic composition. Their grain size and space-filling is very similar to the above described Hungarian bauxites. Large curved kaolinite flakes, probably of diagenetic origin, were found in the Bedarieux bauxite (Figure 10).

Other bauxites of Cretaceous age from the Mediterranean bauxite belt differ significantly from the above if compressional tectonic activity affected them after their formation. These bauxites, which have a boehmitic-diasporic composition, had their bulk porosity lowered to 5–10%. According to our SEM studies their grain size varies from 0.2 to 5μm. These bauxites have lost their original stack-type space-filling and with compaction a uniform space-filling developed in which the micropores became smaller then the crystal grains. We regard it as a uniformly microporous space-filling.

Stronger compression leads to a uniformly compacted space-filling where the individual crystals are closely interlocked. This can be seen in the bauxite of Megara, Greece (Figure 11). In the Padurea Craiului bauxite, Rumania, 1- to 5-μm large euhedral diaspore crystals were observed which are embedded in a dense, fine-grained groundmass (Figure 12).

The Cenomanian bauxite sample from the West Turgai region, USSR, represents a special case. It consists of loosely packed gibbsite plates connected by a fine network of halloysite needles, as determined by EDAX (Figure 13). Many open cavities remain within this framework-type space-filling giving this bauxite a bulk

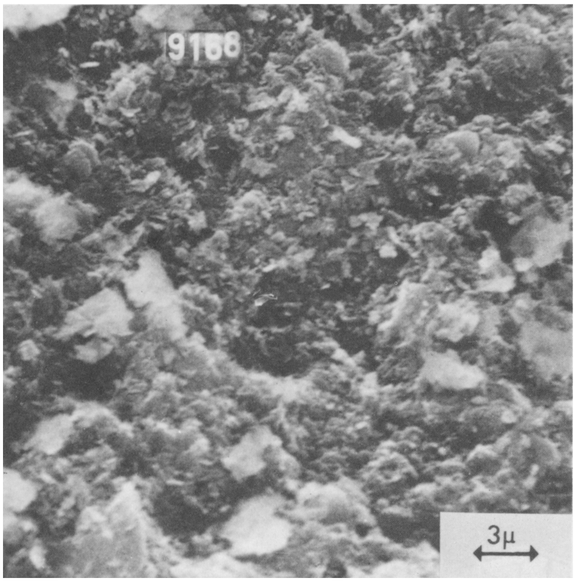

Fig. 7. Paleocene karstic bauxite, Deáki puszta near Nyirád, Hungary. 3000×.

porosity of 20 to 30%. The bauxite has a relatively high strength due to the strong connecting effect of the halloysite network. The region remained tectonically calm after bauxite formation, which explains why the bauxite preserved such loose packing even below an overburden of 20 to 60 m. This is a special type of karstic bauxite deposit, differing from all the karstic bauxites described before and which belong to the so-called "mediterranean-type." We call it the "kasachstanian-type" (Bárdossy, 1973). The physicochemical influ-

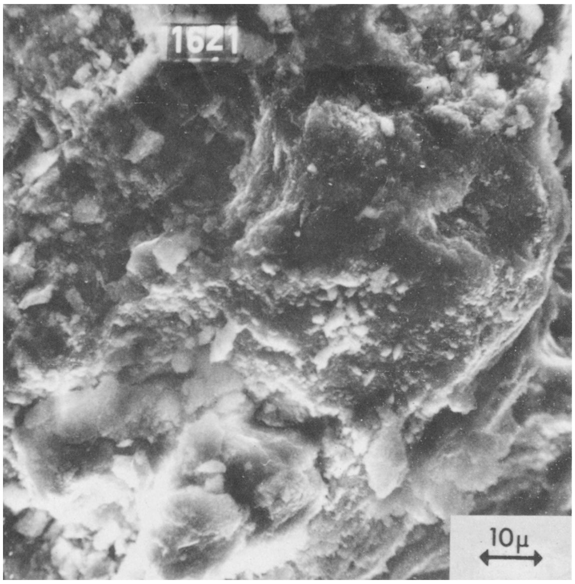

Fig. 8. Eocene bauxitic clay, Ujfeltárás mine near Gánt, Hungary. 1000×.

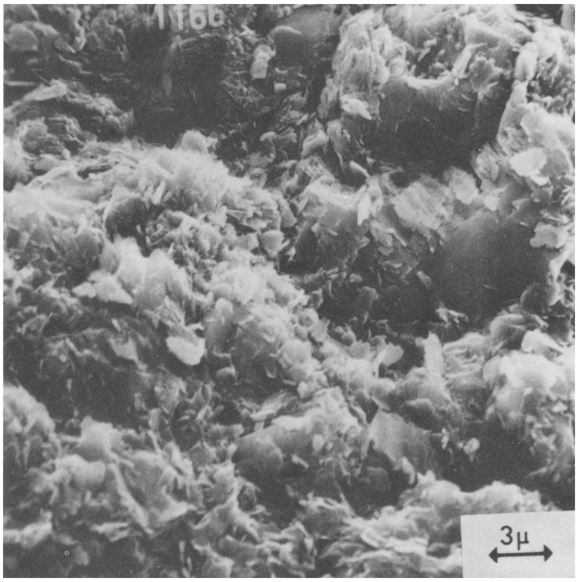

Fig. 9. Paleocene karstic bauxite, Iharkút, Hungary. 3000×.

ence of the carbonate environment was less here, while in situ bauxitization was more effective. This resulted in more effective leaching of the bauxite, and in better developed crystallinity of the bauxite minerals. We interpret it as a transition type toward the lateritic type of bauxite deposits. This geologic interpretation is reflected in the SEMs of the sample when compared with the micrographs of the lateritic bauxites.

Continuing with increasing geologic time, the upper Jurassic bauxites of the Chalchidike peninsula, Greece, follow (courtesy of S. E. Papestawrou). The deposits

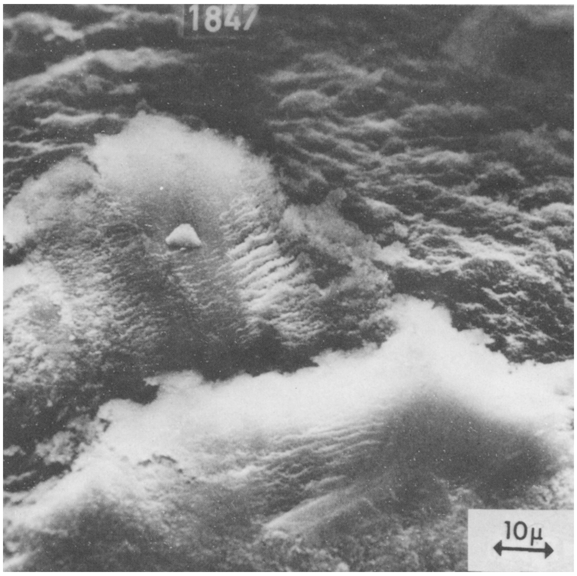

Fig. 10. Kaolinite in Senonian karstic bauxite, Bédarieux, France. 1000×.

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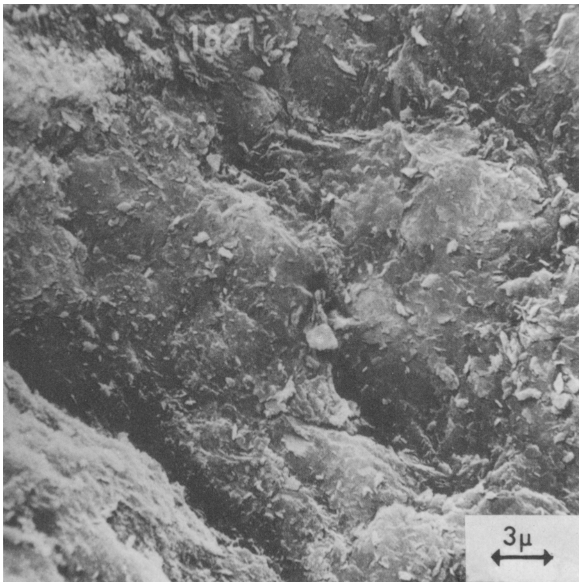

Fig. 11. Albian karstic bauxite, Megara mine, Greece. 3000×.

were affected by strong tectonism and by low-temperature (200–300°C) metamorphism. The overwhelming influence of combined tectonic and metamorphic effects is reflected by the changed grain size and space-filling of these bauxites. Their porosity dropped to 1–4% and they recrystallized into diaspore, chamosite, and corundum as detected by X-ray powder diffraction. Diaspore crystals of 1 to 20 μm size are seen (Figure 14). They are well ordered and have perfect crystal faces and edges. The recrystallization occurred under pressure, after which very few cavities were left between the crystals. We call this a "crystalline-webby"

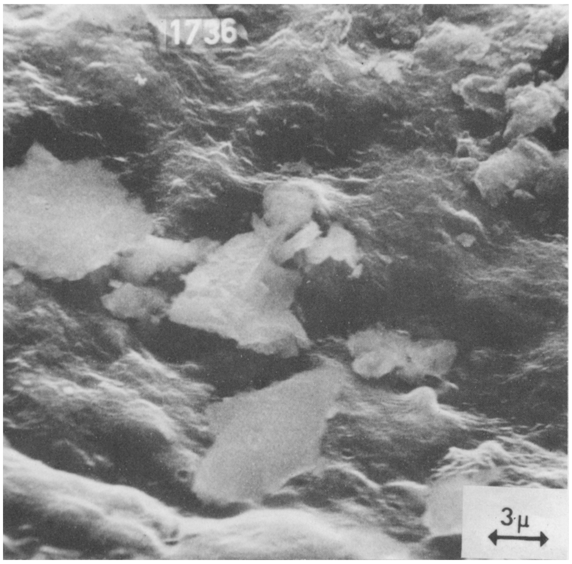

Fig. 12. Neocomian karstic bauxite, Padurea Craiului, Rumania. 3000×.

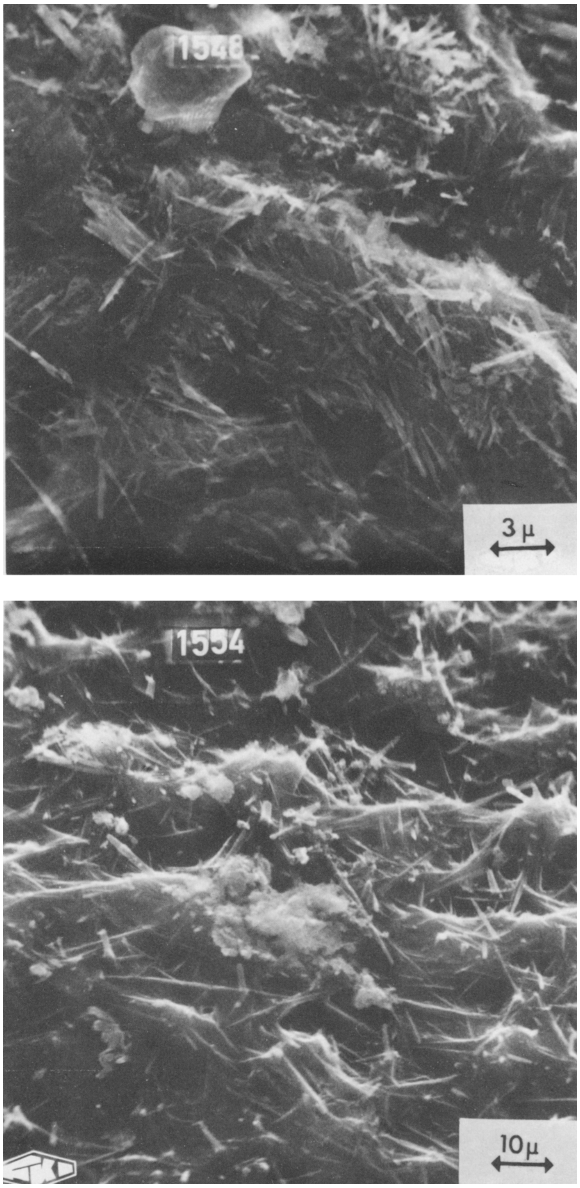

Fig. 13. Cenomanian karstic bauxite, West Turgai region, USSR. A: 3000×; B: 3000×.

space-filling. The chamosite crystals have the same size, but their shape and surface is irregular (Figure 15).

The bauxite from Zarzadilla de Totana, Betic Cordillera Mountains, Spain, is presumably of Dogger age, but it was much less affected by tectonic compression than the foregoing Greek bauxite. The most frequent grain size is 0.2 to 1 μm. The space-filling is uniformly compacted (Figure 16). Most crystallites show flat faces, but their edges are generally irregular. The crystallinity has not yet become perfect.

The Triassic bauxites of Podlipa, Slovenia, and Gornje Polje, Montenegro, both in Yugoslavia, are sim-

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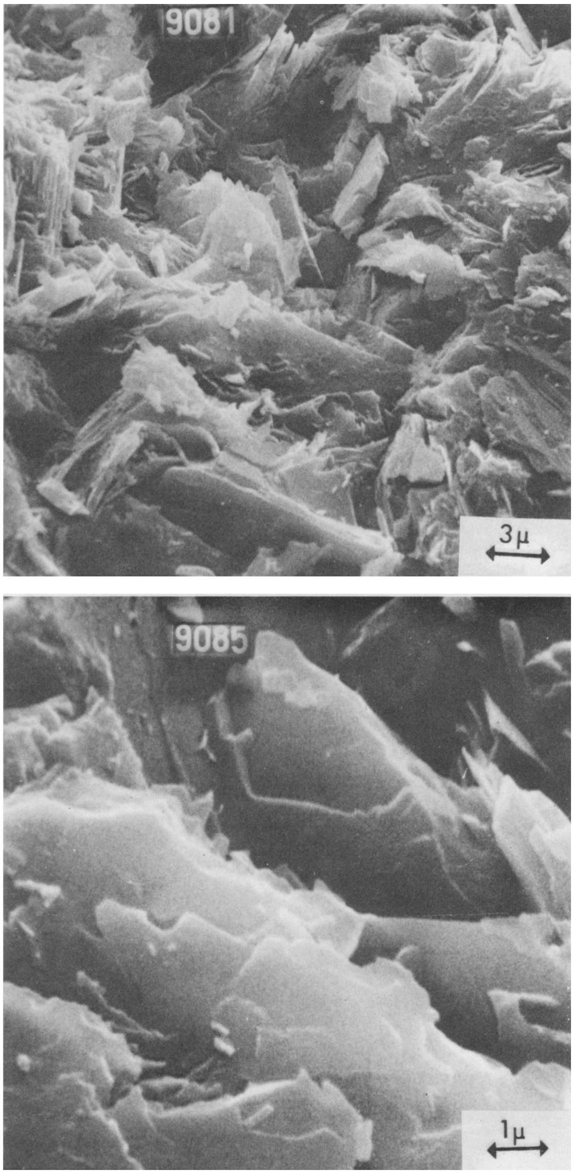

Fig. 14. Kimmeridgian karstic bauxite, Chalkidike-peninsula, Greece. A: 3000×; B: 10,000×.

ilar. Medium strong tectonic activity occurred after bauxite formation. They have been compacted with a bulk porosity of 1 to 5%. Their most frequent grain size is 0.5 to 2μm. The space-filling is uniformly compacted. Both bauxites have oolitic and pisolitic macrotextures. These features are scarcely observable on the SEMs. At some places large kaolinite crystals of secondary origin were observed in the Podlipa bauxite (Figure 17), in which some of the closely packed kaolinite "books" are slightly curved.

The upper Permian bauxites of the Tap-Na region, Vietnam, were affected by very strong compressional tectonism. The deposits were so strongly folded that in

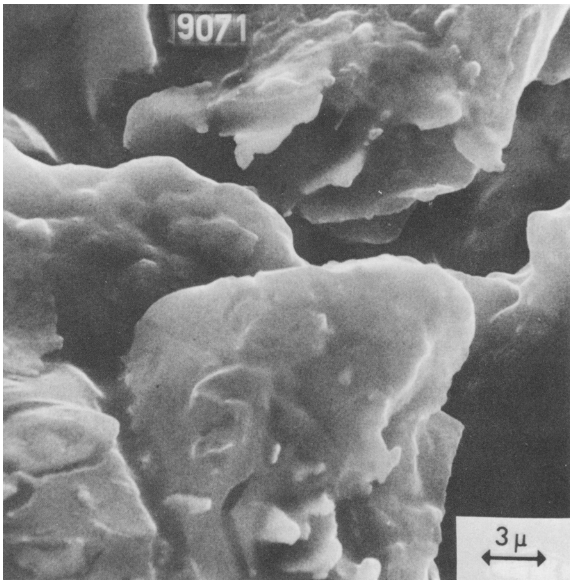

Fig. 15. Kimmeridgian karstic bauxite, Chalkidike-penninsula, Greece. 3000×.

some places they stand vertically or are overturned. They are recrystallized into diaspore and even some corundum was formed. Their porosity is only 1 to 4%. The size of the crystals which have well-developed faces and edges averages 5 to 50 μm. The crystals are grouped into sheaves in parallel orientation although they were displaced irregularly. This produces a webby (weblike) microtexture (Figure 18). At some places less perfectly developed chamosite crystals can be seen.

The Permian overburden was partially eroded during

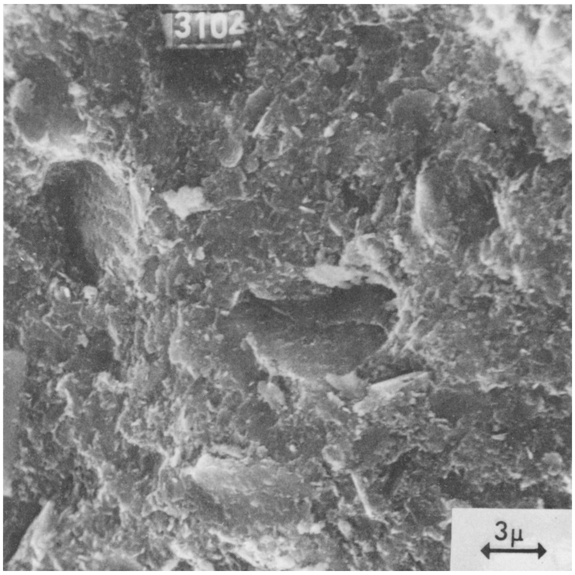

Fig. 16. M. Jurassic/?/karstic bauxite, Zarzadilla de Totana, Spain. 3000×.

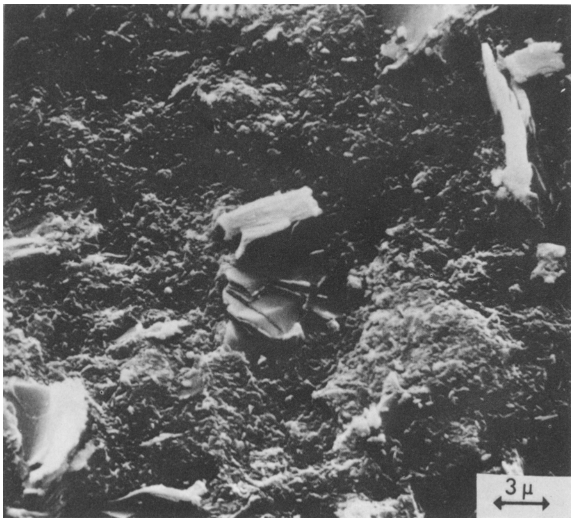

Fig. 17. M. Triassic karstic bauxite, Podlipa, Slovenia, Yugoslavia. 3000×.

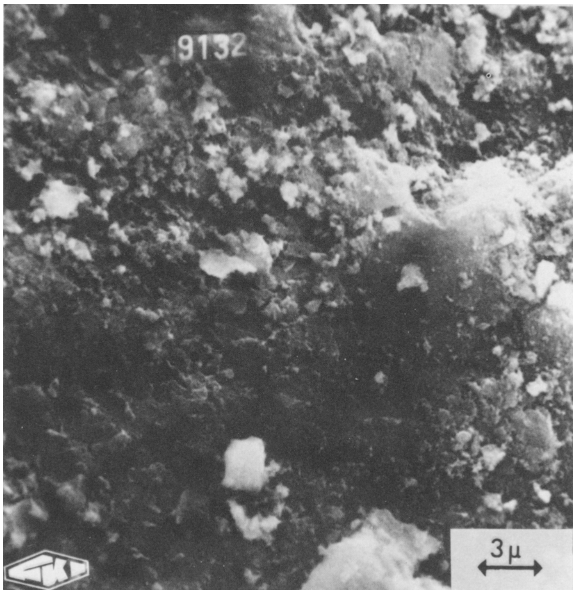

Fig. 19. Redeposited Permian karstic bauxite, Tap-Na, Vietnam. 3000×.

the Neogene, exposing deposits to the surface. They were eroded also, after which their pebbles and boulders accumulated in the valleys forming a special type of redeposited secondary alteration of these bauxites. Consequently, most of their initial chamosite content was altered into gibbsite, hematite, and chloritoid. Our sample No. 7 was collected from such a deposit. Here the surface of the large older crystals is covered by small flaky crystals of 0.2 to 1 μm size. Many small cavities are due to leaching. We call this a secondary leached space-filling (Figure 19). This is a good illustration of how secondary surface alteration can change the porosity, grain size and space-filling of older bauxites.

The Middle Carboniferous bauxites from Missouri (here called diaspore) and from the Gun district, China, are very similar. They have a primary diasporic composition formed by a "digestion" and recrystallization under reducing conditions as described by Keller (1968, 1976). No tectonic events occurred after the bauxites were formed in Missouri and only weakly in Gun. The

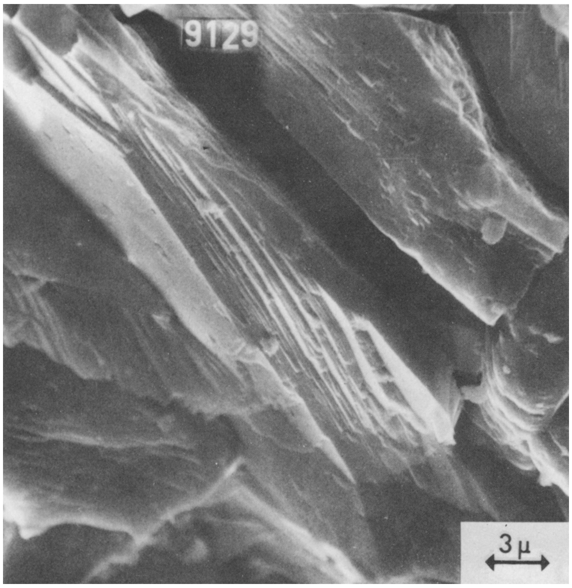

Fig. 18. U. Permian karstic bauxite, Tap-Na, Vietnam. 3000×.

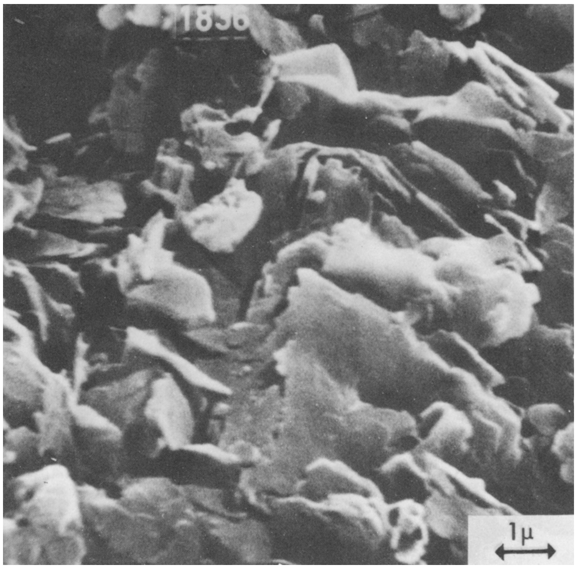

Fig. 20. M. Carboniferous karstic bauxites, Owensville, Missouri, USA. 3000×.

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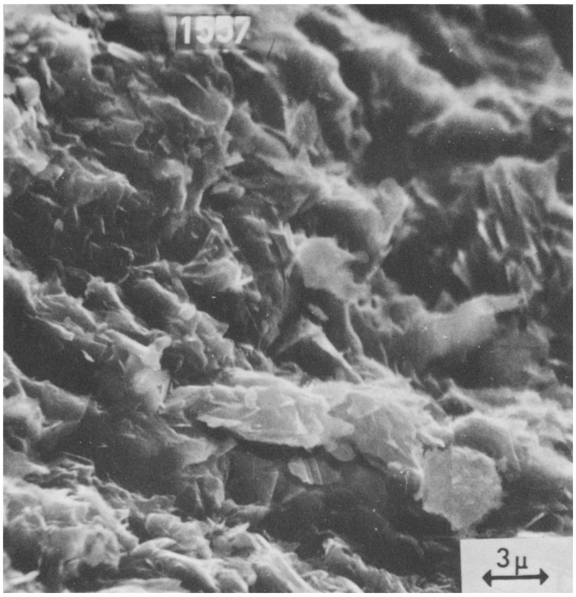

Fig. 21. M. Carboniferous karstic bauxite, Gun-region, China. 3000×.

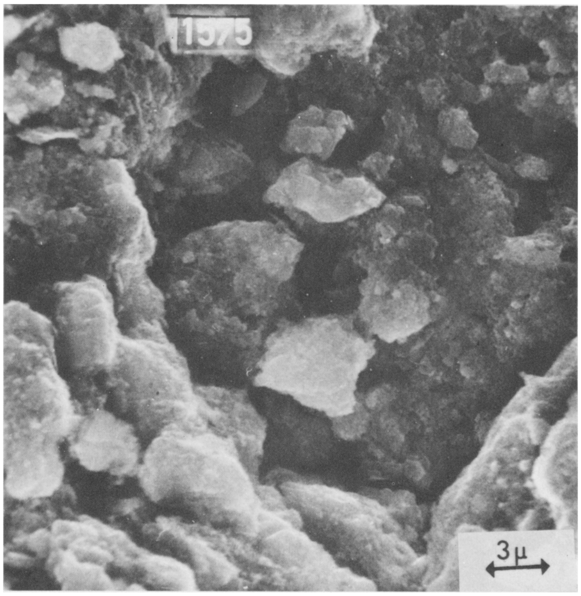

Fig. 23. M. Devonian karstic bauxite, North Ural Mts. USSR. 3000×.

most frequent grain size is 1 to 3 μm. The diaspores of the Missouri sample are not perfectly shaped, most of them have lacy edges (Figure 20). The Chinese bauxite shows better developed diaspore crystals (Figure 21). Both bauxites have a webby microtexture. Note the remarkable similarity of our Figure 20 and of Keller's Figure 19 (part II, 1976). These two bauxites illustrate well that primary diaspore formation under surface conditions produces quite different grain size, crystallinity, and microtexture, compared to the diasporic bauxites formed under tectonic pressure. Diaspore may be recrystallized under surface temperature and pressure (W. D. Keller, personal communication, American Mineralogist, in press).

The lower Carboniferous bauxites of the Tyman Mountains, USSR, have remained tectonically calm since their formation. The overburden is also less than 300 m. Thus the bauxite has preserved its original gibbsitic-boehmitic composition, and maintained a surpris-

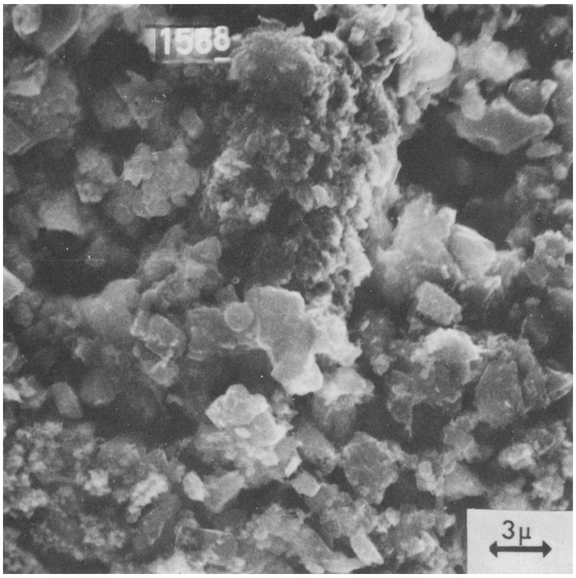

Fig. 22. L. Carboniferous karstic bauxite, Tyman Mts., USSR. 3000×.

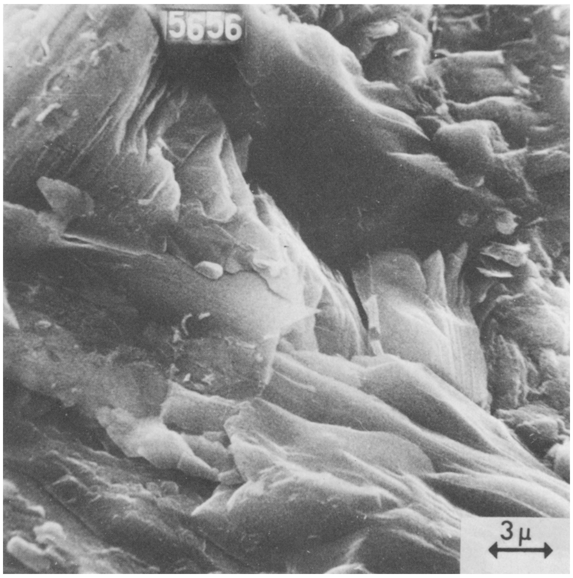

Fig. 24. Lateritic bauxite, Fria, Guinean Republic. 3000×.

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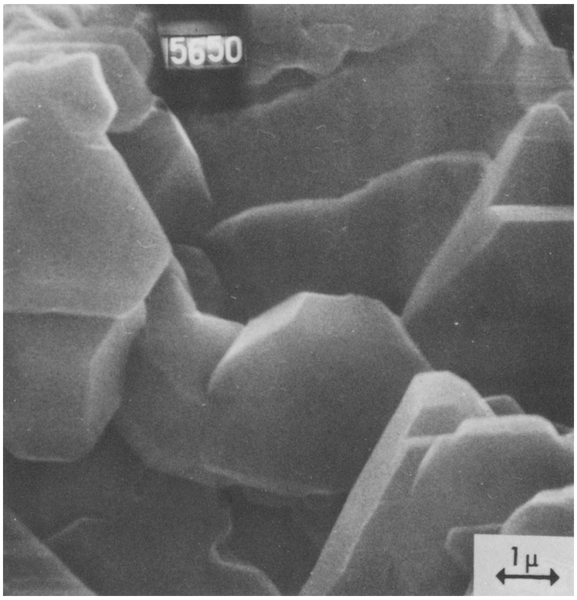

Fig. 25. Lateritic bauxite, Fria, Guinean Republic. 10,000×.

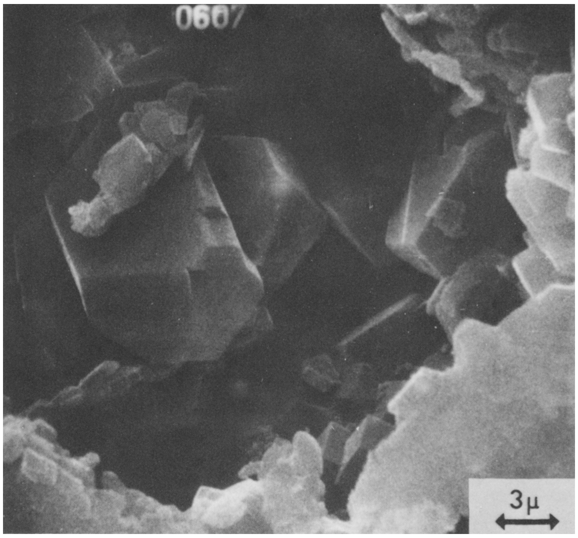

Fig. 27. Lateritic bauxite, Serra do Mantiqueira, Devona deposit, Brazil. 3000×.

ingly high porosity (10–20%) despite its age (340 my). The grain size is slightly larger than that of similar Mesozoic bauxites (1 to 3 μm). The space-filling is with stacks or alternatively is uniformly microporous (Figure 22). The crystals are better developed morphologically than their Mesozoic counterparts, but are far from the perfection of the crystals occurring in the Vietnamese bauxites.

The middle Devonian bauxites of the North Ural Mountains, USSR, were compacted as a result of tectonic compression. At many places perfect diaspore crystals occur, Bushinsky (1975). According to Beneslavsky (1963, 1974) the formation of diaspore occurred here as diagenesis by leaching of the original bauxite. This leaching was observed by us also on some of our SEMs (Figure 23). The most frequent grain size was determined as from 0.2 to 5 μm.

LATERITIC BAUXITES

All of the samples of the 18 lateritic bauxites investigated came from surface deposits with either no overburden or less than 10 m. Furthermore, no tectonic

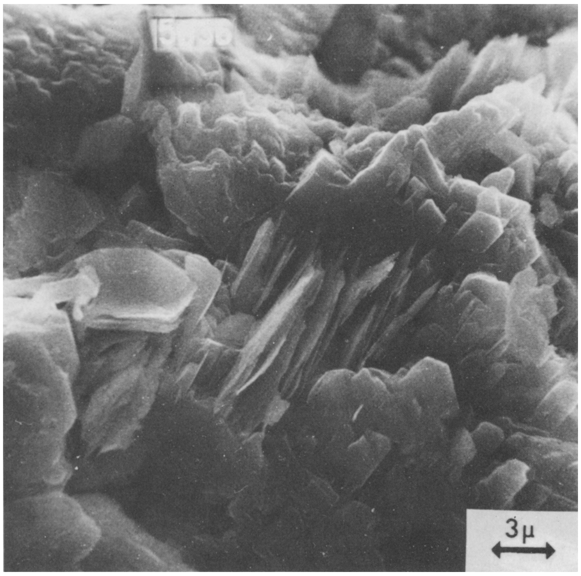

Fig. 26. Lateritic bauxite, Fria, Guinean Republic, 3000×.

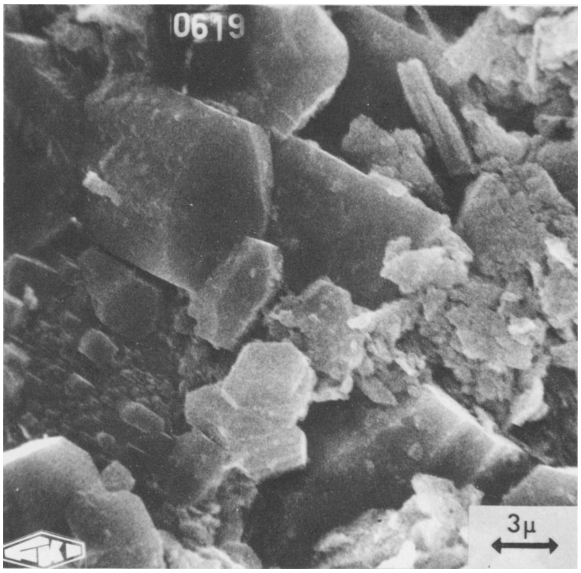

Fig. 28. Lateritic bauxite, Pocos de Caldas, Brazil. 3000×.

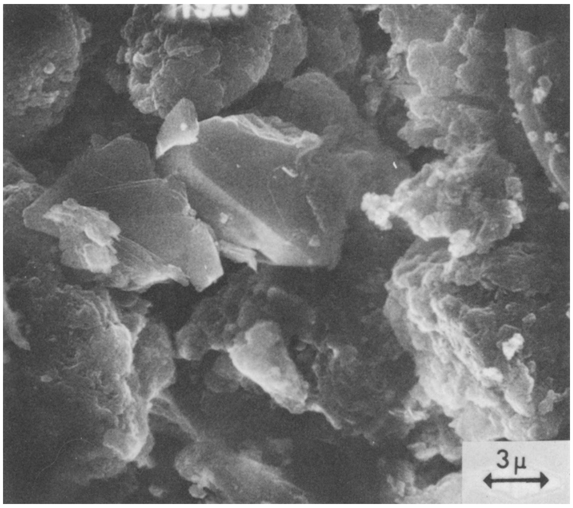

Fig. 29. Lateritic bauxite, Panchpatmali plateau, Orissa, India. 3000×.

pressure affected them. Their ages cannot be determined as exactly as that of the karstic bauxite deposits. What we know for certain is that they are not older than upper Cretaceous and that they are not younger than Pliocene. Only the samples from the Guinean Republic, and from Minas Gerais, Brazil, may be younger, as laterization continues there into the present.

Fourteen samples came from "high-level" deposits at altitudes ranging from 400 to 1900 m above sea level. Four samples were collected from "low-level" deposits at altitudes from 20 to 100 m. Several authors indicated differences in chemical and mineralogical composition, and macrotexture, between the high-level and

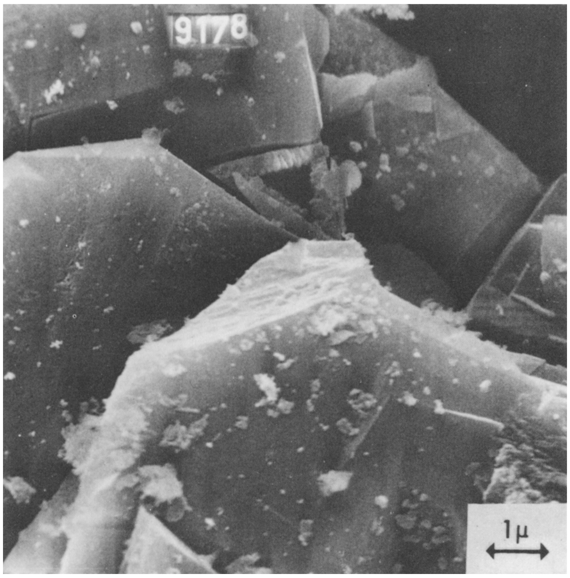

Fig. 30. Lateritic bauxite, Dhangarwadi plateau, Maharashtra, India. 10,000×.

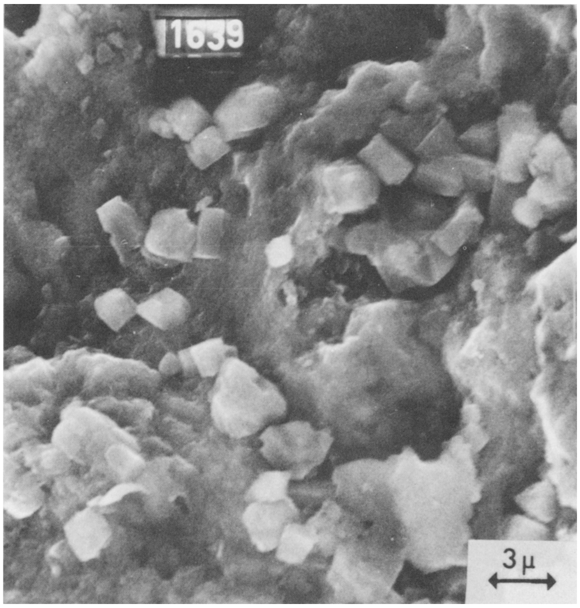

Fig. 31. Lateritic bauxite, Kibi deposit, Ghana. 3000×.

the low-level deposits. For instance, high-level deposits are predominantly gibbsitic, whereas several low-level deposits have a mixed gibbsitic-boehmitic composition. In the following, we also try to differentiate these two types of deposits by SEMs.

High-level deposits

High-level deposits are characterized by strong leaching high above the groundwater table, by mobilization of most elements, and by reprecipitation. Relict macrotextures commonly were formed this way. One of the best examples exhibiting relict macrotexture is the bauxite from Fria, Guinean Republic. We observed in the mine that the bauxite preserved the original stratification of its parent rock, a Gothlandian, graptolitic slate welding its macrotexture. The SEM investigation revealed an extremely large grain size; gibbsite of 10 to 30 μm size are most frequent, but some crystals of 50 to 100 μm in size were observed. The crystal forms are almost perfect. In most cases they are plates (Figure 24), more rarely somewhat thicker pseudohexagons (Figure 25), or thin lamellae (Figure 26). The bauxite has a crystalline-webby microtexture, built up by parallel-oriented gibbsite crystals forming sheaves, the latter oriented in all directions. The sheaves are tightly packed so that cavities occur only between them. This results in a relatively low porosity and high degree of compactness compared with other lateritic bauxites.

Similar high-level bauxites occur in Minas Gerais State, Brazil. Here the parent rock was nepheline syenite. The samples collected from the Serra do Mantiqueira mountains contain almost perfect gibbsite crystals, but here more equidimensional pseudohexagons

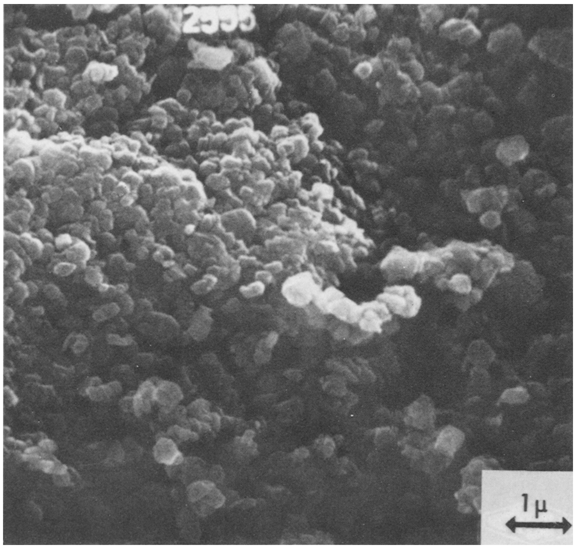

Fig. 32. Lateritic bauxite, Nyinahin hills, Ghana. 10,000×.

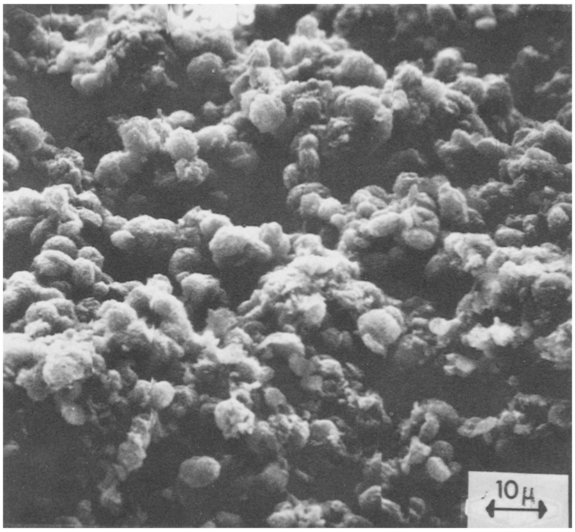

Fig. 33. Lateritic bauxite, Nyinahin hills, Ghana. 1000×.

prevail (Figure 27). The grain size is most frequently between 0.5 to 20 μm. The space-filling is more like a loose framework type, and the porosity is higher (30–40%) than in the Fria bauxites. Large macrocavities can be observed by the unaided eye and bauxite may be called vesicular. At Pocos de Caldas very similar bauxites occur. In Figure 28 large gibbsite crystals are seen, between which are small, irregularly shaped grains of goethite.

The two samples collected in the Eastern Ghat Mountains, India, are also similar to the foregoing ones. The most frequent grain size is 10 to 50 μm, but on the walls of cavities there are gibbsite crystals as large as 1 mm. The gibbsite crystals are extremely well developed whereas the goethite and hematite grains are much smaller and have irregular forms (Figure 29). Strong leaching produced a system of connected open cavities and a framework-type space-filling. Here the parent rocks mainly were Precambrian khondalites whose original structure was preserved by the bauxite.

In a second group of high-level deposits mainly macropisolitic and collomorphous macrotextures occur. Their parent rocks were generally basalts, dolerites, and basic metavulcanites (a little more basic than the parent rocks of the foregoing group). It is significant that this big difference in macrotexture was almost not recognizable in the SEMs.

The sample from the Dhangarwadi Plateau, India, showed almost the same large grain size (2 to 70 μm) and perfect crystallinity as the foregoing samples (Figure 30). Note the very small, irregular goethite flakes at the surface of the large gibbsite crystals. The space-filling in some places is of the framework-type, at other places, crystalline-webby.

The samples from Kibi and Nyinahin region, Ghana, are vesicular and have a typical collomorphous macrotexture. The most frequent grain size is 1 to 10 μm, and the crystals are euhedral. In the Kibi sample small prismatic crystals were found in places (Figure 31). In the Nyinahin bauxites even smaller but well-crystallized gibbsites occur (Figure 32). Strong leaching produced a framework-type space-filling with a network of connected cavities (Figure 33). Similar features were found in the bauxite sample from the Sangaredi Plateau, Guinean Republic.

The two samples from Mali have a typical macropisolitic macrotexture which is also observable on the SEMs (Figure 34). Note the frequency of curved surfaces and the dense packing of the grains between the relatively large cavities. The walls of the largest cavities are covered by euhedral crystals of gibbsite 1 to 3 μm in size (Figure 35). Note the rounded edges of most crystals. The groundmass has only a 0.5 to 2 μm size, the space-filling is collomorphous-spongy. In sample "E" fine halloysite fibers were observed (Figure 36).

Low-level deposits

Low-level deposits are represented by four samples. The sample from the Weipa deposit, Australia, has a typical pisolitic macrotexture. The parent rock is an arkosic sandstone. The bauxite is gibbsitic, with 7 to 10% boehmite. We broke the pisolites and studied their inner parts by SEM. A framework-type space-filling was observed (Figure 37). The crystals are not perfectly developed, and many faces are irregular in shape. The grain size averages from 0.5 to 10 μm. At some places large cavities occur which are filled with gibbsite crystals of secondary origin (Figure 38). They are much larger than the grains of the surrounding groundmass

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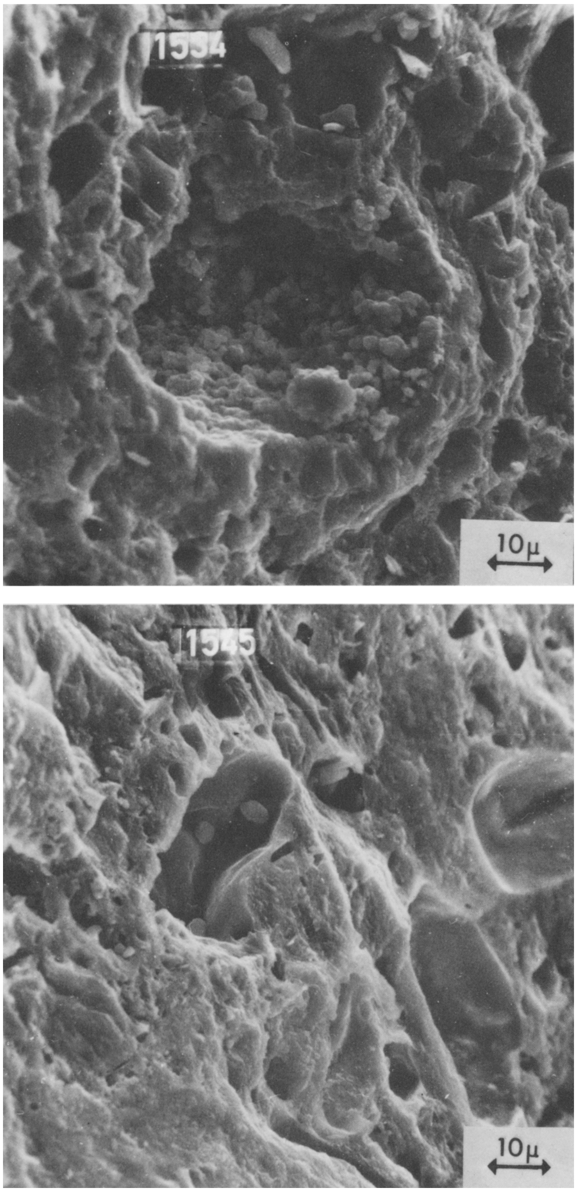

Fig. 34. Lateritic bauxite, near Bamako, Mali. A: 1000×; B: 1000×.

and are almost perfect in crystallinity. We studied also the surfaces of the pisolites by SEM, and found that they are generally covered by hematite flakes 0.1 to 1 μm in size.

The bauxites of the Kutch Peninsula, Gujarat, India, were formed from basalts. The sample from the Nandra deposit is essentially gibbsitic, and has a collomorphous macrotexture. The microtexture, observed by SEM, is uniformly microporous. The grain size varies from 0.1 to 3 μm and the gibbsite crystals are not perfectly developed. Well-developed gibbsite crystals occur only in large cavities (Figure 39). Note the peculiar lacy edges of the gibbsite plates.

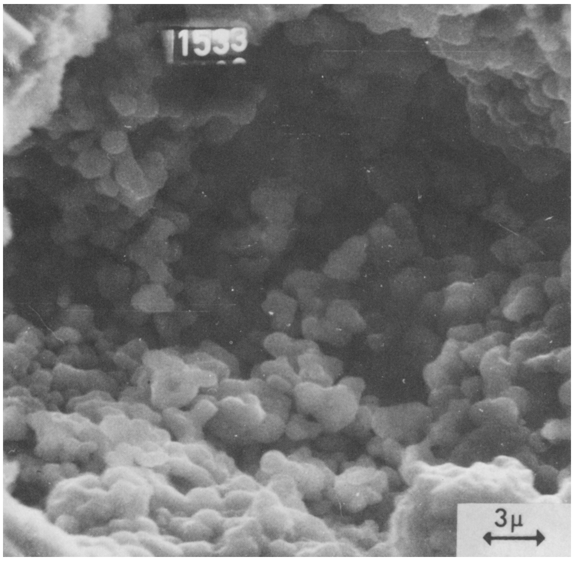

Fig. 35. Lateritic bauxite, near Bamako, Mali. 3000×.

The sample from the Saran deposit on the Kutch peninsula has a pisolitic macrotexture and contains 33% gibbsite, 34% diaspore and 9% boehmite. The diaspore was formed at surface conditions presumably when the deposit was covered during the Miocene by some meters of marshy sediments. Reducing humic solutions leached most of the initial iron content and the mobilized alumina recrystallized as diaspore. The bauxite has a grain size of 0.2 to 1 μm. Cavities are filled with the secondary, well-developed diaspore crystals (Fig-

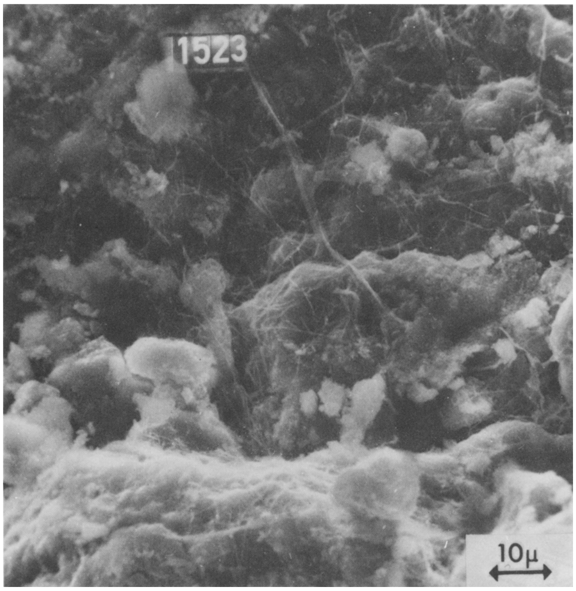

Fig. 36. Lateritic bauxite, near Bamako, Mali. 1000×.

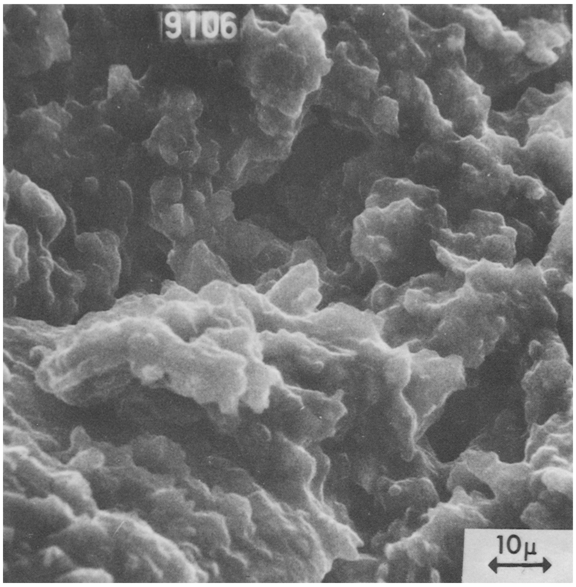

Fig. 37. Lateritic bauxite, Weipa, Australia. 1000×.

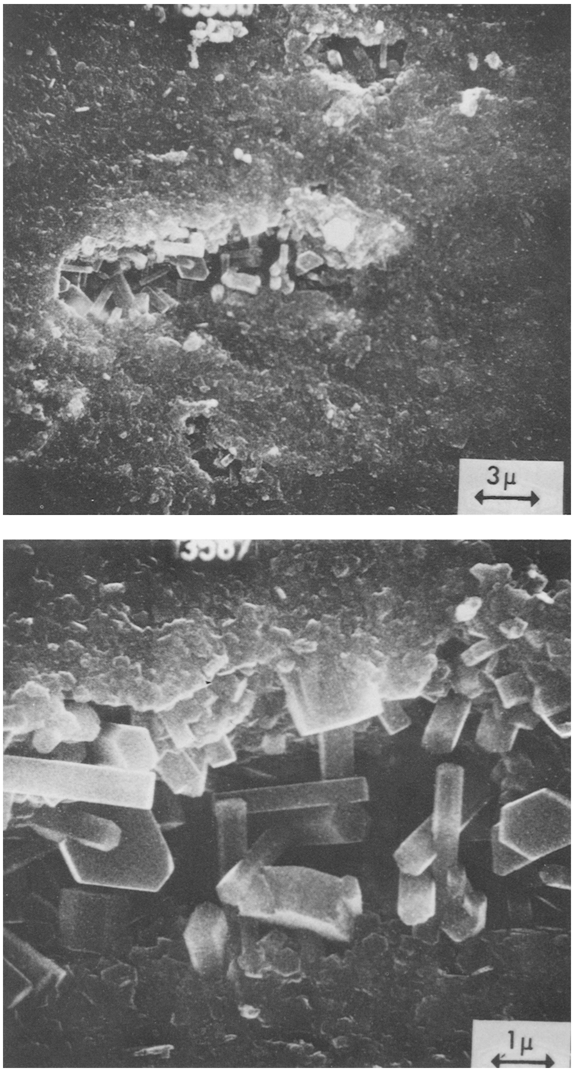

Fig. 38. Gibbsite crystals in bauxite, Weipa, Australia. A: 3000×; B: 10,000×.

ure 40). This type of diaspore formation in lateritic bauxites is very rare.

The bauxites of Kassa-island, Guinean Republic, were formed by the alteration of nepheline syenites. Leaching conditions were extremely favorable and thus a relict macrotexture similar to high-level bauxites developed. Our SEM investigations revealed a framework-type microtexture with a grain size, smaller than in the high-level bauxites, between 1 to 10 μm. The bauxite is predominantly gibbsitic, but the gibbsites are not perfectly developed and their edges are irregularly shaped (Figure 41). Compare this micrograph with the Brazilian high-level bauxites formed from the same type nepheline syenite (Figures 27, 28). In both places mainly direct laterization occurred, but the difference in altitude produced differences in grain size and crystallinity.

TICHVIN-TYPE BAUXITES

This type is represented by only one sample collected from the Sinionskoe open pit mine of the Tichvin region, USSR. The age of the deposit is lower Carboniferous. Since there was no tectonic compression after the bauxites were formed, the gibbsitic-boehmitic composition and a relatively high porosity (10 to 30%) has been preserved. The sample has an arenitic macrotexture. Its microtexture revealed by SEM is uniformly microporous. The grain size varies from 0.5 to 2 μm. The grains are generally irregular and well developed, platy gibbsite crystals are rarely observed (Figure 42). Because only 0.3% of the world's bauxite reserves belong to this type of deposit, no further samples were studied.

CONCLUSIONS

The initial grain size of bauxite minerals varies from 0.05 to 100 μm, but secondary crystals may reach millimeter size. The smallest grain size is in the young, surface-deposits of the karstic type. In this group the grain size increases only slightly with age, and with the load pressure of overburden which does not exceed 300 m in thickness. Strong compaction and recrystallization begin with growing tectonic pressure giving rise to grain sizes up to 50 μm. Low temperature metamorphism (less than 300°C) leads to further crystal growth and compaction. At higher temperatures, bauxites recrystallize into emery.

Most of the high-level lateritic bauxite deposits show extremely large grain sizes, up to 100 μm, and large single crystals in cavities may reach millimeter size.

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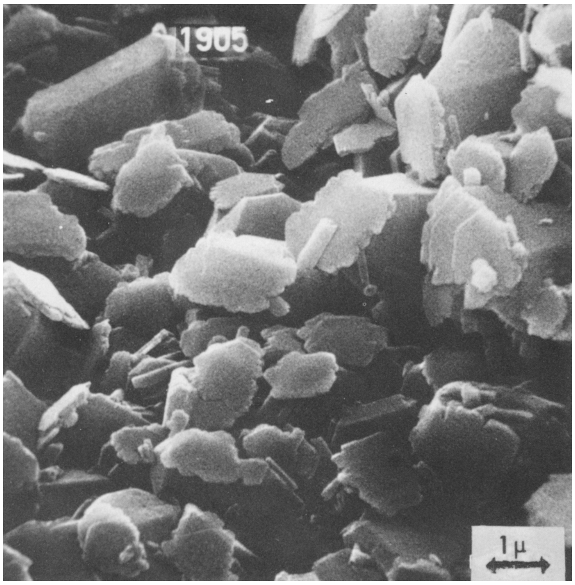

Fig. 39. Lateritic bauxite, gibbsite in cavity, Nandra, Gujarat, India. 10,000×.

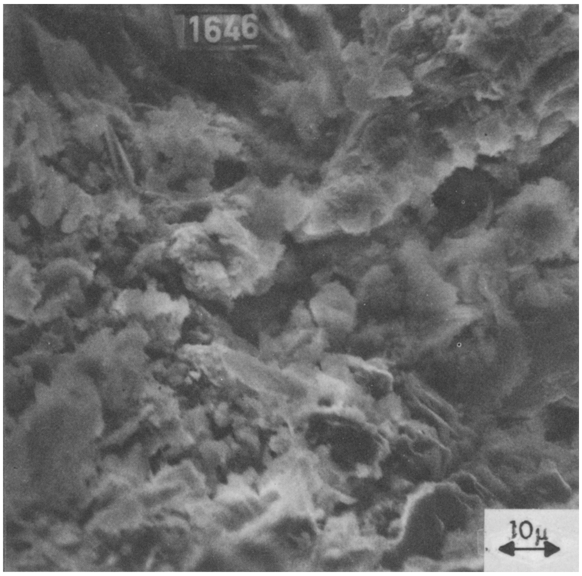

Fig. 41. Lateritic bauxite, Kassa-Island, Guinean Republic. 1000×.

The grain size of low-level bauxites averages from 1 to 10 μm, but large cavity fillings also may occur.

In our opinion, the small grain size of the karstic surface deposits is the result of a physicochemical retardation effect due to the carbonate environment which slows down the growth of the bauxite minerals. On the other hand, the formation of very large crystals in the high-level deposits was produced by extremely good leaching conditions at neutral to slightly acid pH values. The elements of the bauxite minerals were mobilized and reprecipitated almost at the same place leading to more perfect crystallization.

Gibbsite and diaspore form the largest crystals, while boehmite generally remains below 5 μm. In surface deposits, hematite and goethite rarely grow to over 1 μm. In two samples, both needle- and fiber-shaped halloysite were found by SEM. We do not know the special conditions that favor the formation of this mineral.

The shape of the bauxite minerals varies from irregular, through imperfect, to perfectly developed crystals. This is in good accord with our former investiga-

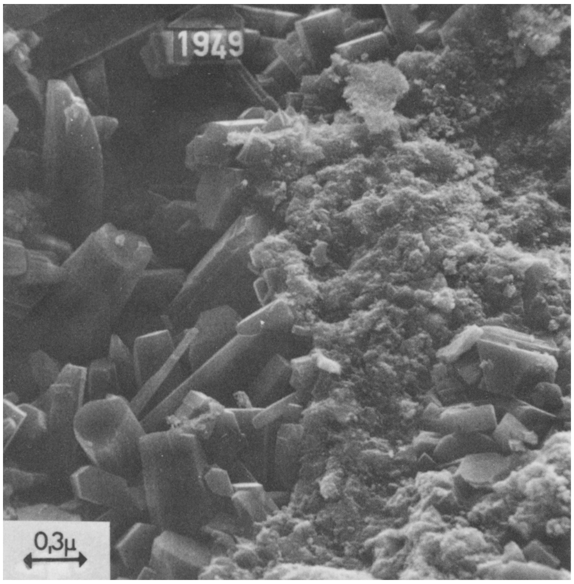

Fig. 40. Lateritic bauxite, diaspore in cavity, Saran, Gujarat, India. 30,000×.

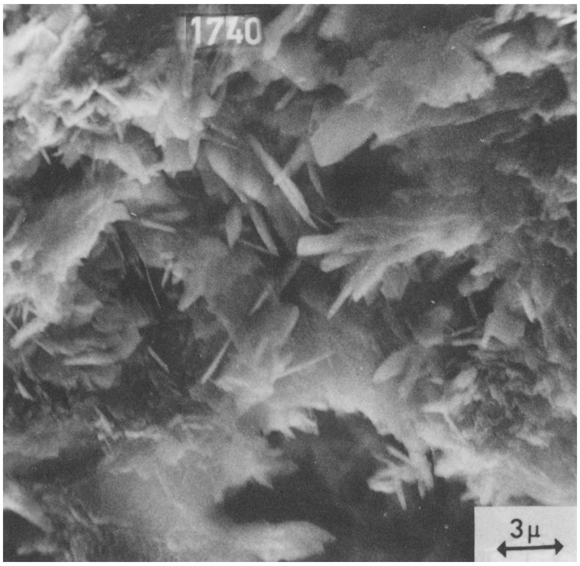

Fig. 42. Tichvin-type bauxite, Sinionskoe mine near Tichvin, USSR. 3000×.

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tions revealing significant differences in the crystallinity of the main bauxite minerals (Bárdossy et al., 1976).

Few of the macrotextures observed with the naked eye are also found on the SEMs. On the other hand, several types of microtexture and space-filling were distinguished by SEM. The following types were found in the studied samples: "stacky"; uniformly microporous; uniformly compact; crystalline-webby; framework-type; collomorphous-spongy; and secondarily leached space-filling.

All of the karstic surface deposits which were investigated have a stacky space-filling. With increased load pressure of the overburden and long time of growth this changes into a uniformly microporous space-filling. Increasing tectonic pressure leads to further compaction and produces a uniformly compact space-filling. Very strong tectonic compression or low-temperature metamorphism produces a crystalline-webby microtexture as a result of recrystallization of the bauxite minerals. The length of time is not significant; even Carboniferous bauxites may have a uniformly microporous space-filling if the overburden was thin and no tectonic compression occurred after the bauxites were formed.

Most samples from high-level deposits have a framework-type space-filling. The crystalline-webby type is limited to the most recrystallized and relatively compact bauxites. At some deposits uniformly microporous and collomorphous-spongy space-filling also occurs. The reasons for these differences are not yet known.

Part of the low-level bauxites showed a framework-type space-filling, others are uniformly microporous. We presume that this latter one was produced by remobilization of minerals under reducing or marshy conditions.

The genetic resemblance of the "kazachstanian-type" karstic bauxite deposits to the lateritic ones is supported by the SEMs which illustrate a framework-type space-filling and a fairly well developed crystallinity of the bauxite minerals.

Our experiences show that transmission electron microscopy (TEM), scanning electron microscopy (SEM), and electron microprobe studies of bauxites complement each other. Size and shape of single grains are best studied by high magnification TEM. SEM reveals the space-filling and microtexture best, but grain size and shape also can be determined. Textural features and microdistribution of elements are best studied by microprobe. They may be complemented by petrographic microscope studies of thin sections, and by macroscopic observation of hand specimens and entire rock surfaces in mines. A detailed structural-textural study beginning in the mine and finishing at dimensions of TEM furnishes the best clues for any genetic interpretation.

According to our experience information gained by SEM can be used for technological tasks also. A close relation exists between the technological properties and the grain size, space-filling, and degree of crystallinity of bauxites. Significant differences were found in digestion and desilification times of bauxites having the same mineralogical composition, but exhibiting different grain size, crystallinity and space-filling.

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Резюме- Шестьдесят пять образцов боксита разного возраста и происхождения были изучены развертывающим электронным микроскопом. Исследовались только разломанные поверхности образцов. Были изучены размеры и формы индивидуальных кристаллов и агрегатов зерен,также как различные типы микро-текстур и наполнителей межзернового пространства.
Размер зерен меняется от 0.05 µм до 1 мм. Наименьшими являются размеры зерен молодой карстовой залежи боксита,что объясняется физическо-химическим замедляющим эффектом карбонатной среды. Значительные различия были обнаружены при сравнении наполнителей межзернового пространства в бокситах карстовых и латеритовых залежей. Латеритовые залежи высокого и низкого уровней также обнаруживают различия.
Комбинированное использование макроскопических наблюдений,петрографической микроскопии,электронного микрозонда,PEM и TEM обеспечивает наилучшие возможности для интерпретации генезиса бокситов. Исследования с помощью PEM полезны при решении технологических проблем обогащения бокситов.

Kurzreferat- Fünfundsechzig Bauxitproben, verschiedenen Alters und Abstammung, wurden mit "Scanning electron microscopy "(SEM) untersucht. Nur gebrochene Oberflächen der Proben wurden untersucht. Sowohl Größe und Formen einzelner Kristalle und Kern-Aggregate, wie auch verschiedene Typen von Mikrostrukturen und Füllmassen wurden untersucht. Körnchengröße schwankt von 0,05 um bis lmm.Eine junge, karstische Bauxitablagerung hat das kleinste Körnchenausmaß, was auf einen physikalisch-chemischen Verzögerungseffekt der Karbonatumgebung zurückzuführen ist. Bedeutende Unterschiede wurden ent -deckt durch den Vergleich von Füllkapazitäten der karstischen und lateritischen Bauxitablagerungen. Hochliegende und niedrigliegende ,lateritische Bauxitablagerungen zeigen auch Unterschiede. Die besten Anhaltspunkte für irgendwelche genetische Interpretationen von Bauxiten, wurden durch den ver -einigten Gebrauch von makroskopischen Beobachtungen, petographischer Mikroskopie, Elektronen-Mikrountersuchungen, SEM und TEM geliefert. SEM Unter suchungen können angewendet werden, um technologische Probleme der Bauxitbearbeitung zu lösen.

Résumé-Soixante-cinq échantillons de bauxite d'âges et d'origines différents ont été étudiés par microscopie électronique.Seules les surfaces cassées des spécimens ont été l'objet de recherches.La taille et la forme de cristaux individuels et d'aggrégats de grains ont été étudiées,de même que différentes sortes de micro-textures et d'éléments comblant les vides.
La taille des grains varie de 0.05 µm à lmm.La graine de la plus petite taille est celle d'une jeune bauxite karstique,qui s'explique par un effet de retardation physico-chimique du milieu ambiant carbonate.Des différences significatives ont été trouvées en comparant le comblement d'espaces de dépôts de bauxite karstiques et latéritiques.L'usage combiné d'observations macroscopiques,de microscopie petrographique,de microprobe électronique,de S.E.M. et de T.E.M. procurent les meilleurs indices pour une interprétation génétique de bauxites.Les études au microscope électronique aident à résoudre les problèmes technologiques du traitement de la bauxite.