Palaeogene Bauxites of the Transdanubian Range, Hungary (Óbarok and Gánt)

2nd REEBAUX Meeting

FieldTrip Guide

UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA

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Introduction to Bauxite Geology

Bauxites are products of subaerial chemical weathering formed under humid tropical to subtropical conditions and characterized by residual concentrations of hydrous Al, Fe, and Ti. They may be associated with weathering crusts developed in the Intertropical Zone on the surface of silicate rocks (=**lateritic bauxites**), or may occur as more or less continuous, mainly redeposited, soil-like blankets covering the karstified surface of carbonate rocks (=**karst bauxites**) (Bárdossy 1982; Bárdossy & Aleva 1990). For a long time bauxites were considered as mineral raw materials only, and were treated accordingly. The first isolated attempts to consider bauxites as ordinary sedimentary rocks date back to the 1960's and concern mainly those called "karst bauxites". The latest comprehensive review of karst bauxite sedimentology was published in Ecl.Geol.Helv by D'Argenio & Mindszenty in 1995. **Karst bauxites** occurring in otherwise continuous carbonate successions indicate periods of subaerial exposure and humid tropical climate. They can also provide detailed (local, regional and global) paleo environmental information about those periods which - because of non-deposition or erosion - are not represented by marine sediments (~ unconformity- or disconformity-related "lacunae"). Most authors agree that the **source material** of karst-related bauxites is polygenetic. Any igneous, metamorphic, ophiolitic or sedimentary rock, exposed to humid tropical conditions, provides ferrallitic weathering products that may be converted to bauxite when transported to a karst terrain by surface waters or wind, and perhaps mixed with pyroclastics plus residue from in situ weathering of carbonate rocks. Bauxitization may begin already during the transport of the weathered material and continue after deposition. Bauxitization tends to conceal primary depositional structures, due to substantial geochemical/textural changes. However, the karstic environment, because of its particular topography, provides for repeated reworking and short-range (so called parautochthonous) transport of the unconsolidated sediment, resulting in textures resembling those brought about by primary depositional processes. Clear distinction of the two is not always possible, and along with the careful study of the bauxite itself, may also require other pertinent geological information to be considered.

Based on the intensity of post-depositional bauxitization, deposits can be qualified as predominantly autochthonous or allochthonous. In bauxite geology **allochthony** means that the sediment was bauxitized elsewhere and was deposited on its present site after considerable fluvial or mass-movement type transport (Nicolas & Lecolle 1968; Nicolas 1970; Valeton 1972; 1991; Combes 1984, 1990). **Autochthony** on the other hand means that the prebauxitic material was bauxitized in situ as a result of processes similar to **ferrallitization**. This early bauxitization may have been interrupted or not by recurrent (local) small scale (dm to cm) mechanical transport (=parautochthonous redeposition) resulted/accompanied by sheet-wash, soil-creep, little slumps or other small-scale mass-movements on the dissected karst terrain. Autochthony therefore does not necessarily mean that the prebauxitic material is, in itself, exclusively of local origin (i.e; dissolution residue of the bedrock). On the contrary, in most cases there is ample evidence that the prebauxitic material was brought to the karst terrain by wind or water-induced transportation (Nicolas & Lecolle 1968; Nicolas 1970; Mindszenty 1983; Mindszenty et al. 1988, 1991). **Autochthony** is thought to be indicated texturally by in situ segregational or accretional ooids (the outermost crusts of which show a gradual transition towards the surrounding matrix). Non-spherical grains are mainly intraclasts in this group. Matrix and ooids/intraclasts are of identical geochemical facies (see explanation below). In the case of mudstone-type (or pelitomorphic) bauxites, autochthony cannot be recognized on the basis of texture alone.

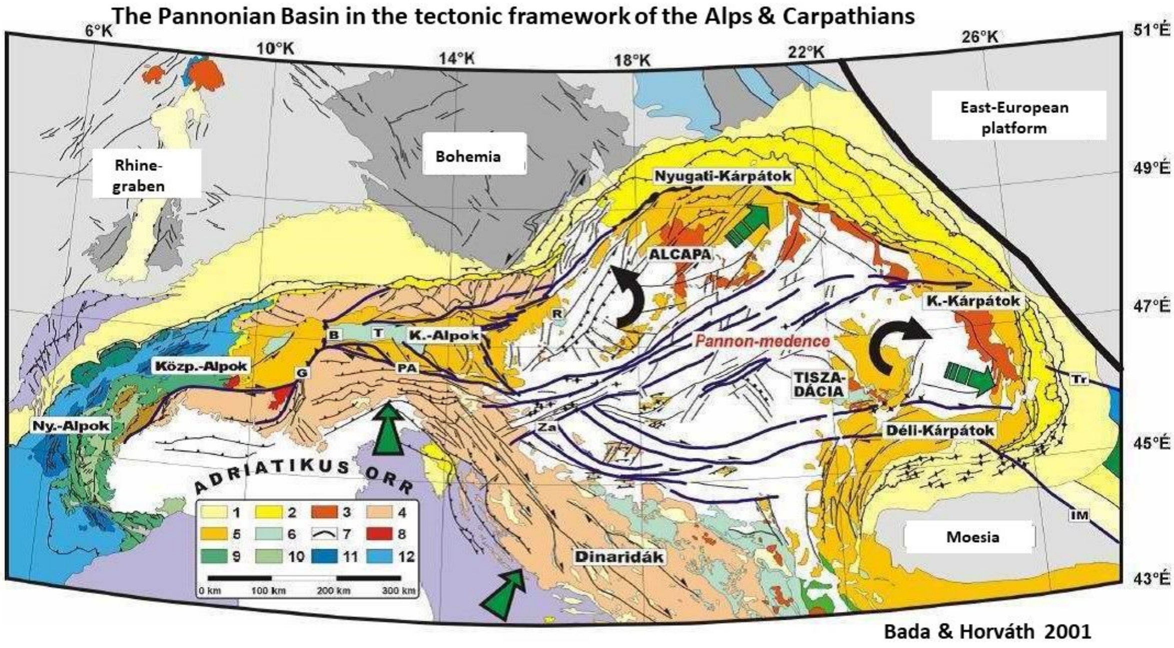
Autochthony on the large scale is reflected by the regular pattern of alumina-enrichment within the deposit (high-alumina bauxite occurring as a rule at places of optimum paleodrainage within the karstic sinkhole (Nia 1967; Balkay 1973; Valeton 1976; Bárdossy 1982). **Allochthony** on the other hand is shown by a generally high diversity of ooids/pisoids and clastic grains (which all have abrupt contacts toward the surrounding matrix), by the presence of bauxite pebbles and by the capriciously changing grade of the ore within the deposit. Very frequently, the geochemical facies of ooids and pisoids varies and is markedly different from that of the matrix. Among the non-spherical grains, non-bauxitic extraclasts also occur in this group. The pattern of alumina enrichment is irregular within the deposit; large-scale cross stratification, graded bedding etc. may be apparent on the macroscopic and microscopic scale. **Parautochthony** (Komlóssy 1967; Bonte 1969; Bárdossy 1982) or "allochtonie relatif" (sensu Combes 1990) is characterized by an apparently clastic texture (with abundant intraclasts), but also with clear signs of in situ formed textural elements (faint accretion rims around intraclasts, etc.) and commonly with a regular pattern of alumina-enrichment on the large scale. There may or may not be a difference between the geochemical facies of matrix and grains. Stratification - if at all - occurs on the microscopical scale only. As pointed out recently by Valeton 1991, allochthony-autochthony-parautochthony are not absolute categories. To qualify a given deposit needs careful study and it is always the predominant characters on the basis of which we may decide whether the bauxite is allochthonous rather than just parautochthonous. Within one and the same deposit there may be parts exhibiting clear signs of autochthony alternating with undoubtedly allochthonous parts. Recognition of the areal distribution of predominantly allochthonous and autochthonous lithotypes may in fact help to understand the sometimes not at all simple story recorded by a given deposit (Combes 1984; Mindszenty 1983, 1984, 1991).

Mineralogy and geochemistry of karst bauxites faithfully records the redox conditions of the depositional environment. Since redox conditions are principally controlled by the relative position of the paleo-groundwater-table (high water-table → stagnant groundwater, reducing conditions; low water-table → unobstructed drainage, oxidizing conditions) karst bauxites are excellent paleotopographic indicators. The geochemistry of the depositional/diagenetic environment of bauxite formation can be characterized at its extremes as "vadose" and "phreatic". **Vadose bauxites** deposited high above the groundwater table, are characterized by equally oxidized nature of matrix and ooids/intraclasts and by predominant hematite and/or goethite as primary iron minerals accompanied by gibbsite and/or boehmite. They are rich in "bauxitophilic" trace elements like V, Co, Ni, Cr, Zr and in some cases also in REEs which are preferentially concentrated at the bottom of the vertical profile. **Phreatic bauxites**, on the contrary, have a less oxidized, (or even reduced), pale-colored matrix, poor in trivalent iron, sometimes accompanied by likewise pale ooids and/or intraclasts. Their main iron minerals are goethite, siderite and/or pyrite, with or without chlorite (mainly chamosite) accompanied by diaspore and/or boehmite as alumina minerals. They may also contain recognizable traces of more or less decayed plant material. Chemical analyses show that phreatic bauxites have a characteristically weak trace element "signal", and no regular distribution of the trace elements can be observed in the vertical profile either. Recent research shows that depositional and diagenetic facies are not necessarily identical. Bauxites deposited in vadose facies under conditions of free drainage may become subject to phreatic conditions (impeded drainage) during and after incipient burial and may therefore be altered mineralogically and geochemically. The response to the changing conditions seems to depend on the degree of lithification (i.e. irreversible mineralization) the sediment attained before burial.

Textures/structures of bauxites and the geometry of the karst morphology they fill may also be informative in the context of the paleorelief. Bauxites found in deep sinkholes of high-level karst terrains, are mainly characterized by in situ formed textural elements whereas those occurring in shallow topographic depressions of low-level karst terrains, may be rich in coarse (pebble-size) transported grains and often show large-scale crossbedding and other sedimentary structures which clearly show that prior to deposition the sediment was subject to considerable transport. Detailed studies of several karst bauxite deposits showed that there was a close correlation between the geochemical and lithological facies of bauxites and the karst morphology they were associated with. Vadose bauxites are generally characterized by the predominance of autochthonous /parautochthonous textures and often fill sinkholes of considerable depth, whereas those qualified as phreatic by their mineralogy and geochemistry often show allochthonous textures and fill a shallow karst relief. The reason for the correlation is obviously the fact that both the geochemistry of the depositional environment and the character of the karst features are essentially controlled by the position of the karst surface as related to the karstic water table: deep vadose karst facilitates early diagenetic processes to take place under conditions of free drainage resulting in vadose bauxites. This is possible only when the depositional environment is situated sufficiently high above the water table. On the contrary, shallow karst relief is expected to form close to the water table where impeded drainage results in the formation of phreatic bauxites.

It follows from the above that **depositional** and **diagenetic facies** are in fact closely related. Bauxites having been deposited in a close-to-phreatic environment are more likely to contain abundant organic matter because the lack of oxygen slows down the otherwise rapid destruction of plant detritus even under tropical conditions. Therefore, much more than their "vadose" counterparts, they are likely to be altered during burial and reflect late-diagenetic phreatic environments (loss of trivalent iron, sideritization or pyritization) It is this correlation between lithofacies, underlying karst morphology and the paleoposition of the depositional environment (as related to the karstic water-table) which makes bauxites so useful in the reconstruction of paleorelief. Detailed studies proved that these principles can usefully be applied when trying to reconstruct the conditions of bauxite formation. Paleogeomorphological reconstructions of bauxitiferous terrains on the regional scale show that the lithological/geochemical facies of bauxites, when combined with the type of the underlying karst morphology, may reveal information about the relative paleo-altitude of larger crustal segments as well.

Paleogeographic reconstructions can be refined considerably by detailed studies of selected bauxite deposits when paying particular attention to (i) the lithofacies of the immediate bedrock/cover and (ii) the nature of the underlying karst. Syn- to postdepositional tectonic events - otherwise possibly overlooked - can be postulated, and in many cases, the “empty” stratigraphic gap can be "filled" by a sequence of climatic and/or tectonic events otherwise not even suspected. Micromineralogical studies have shown that the HCl-insoluble residue of bauxites can provide information also about the geology of the surrounding non-carbonate terraines and thus can be used to monitor the denudation-history of adjacent exposed areas Plate-tectonics scale reconstructions of the paleorelief/paleogeography of bauxitiferous regions show that bauxites - in addition to their obvious economic merit - have quite a lot to offer to sedimentary geology and tectonics as well.



Key:1=Molasse Foredeeps, 2=Flysch-nappes, 3=Calc-alkaline volcanics, 4= Apine and Dinaric carbonates, 5= Inner Alpine and Carpathian nappes. 6=European Hercynian basement (in tectonic windows), 7= Carpathian Klippen-belt, 8= Tonalites, 9=Penninic basement, 10=Coverbeds of the Penninic, 11= Basement of the Helvetics, 12= Cover of the Helvetics, PAL=Periadriatic Lineament

Fig. 1 The visited area in the tectonic framework of the Alps and Carpathians

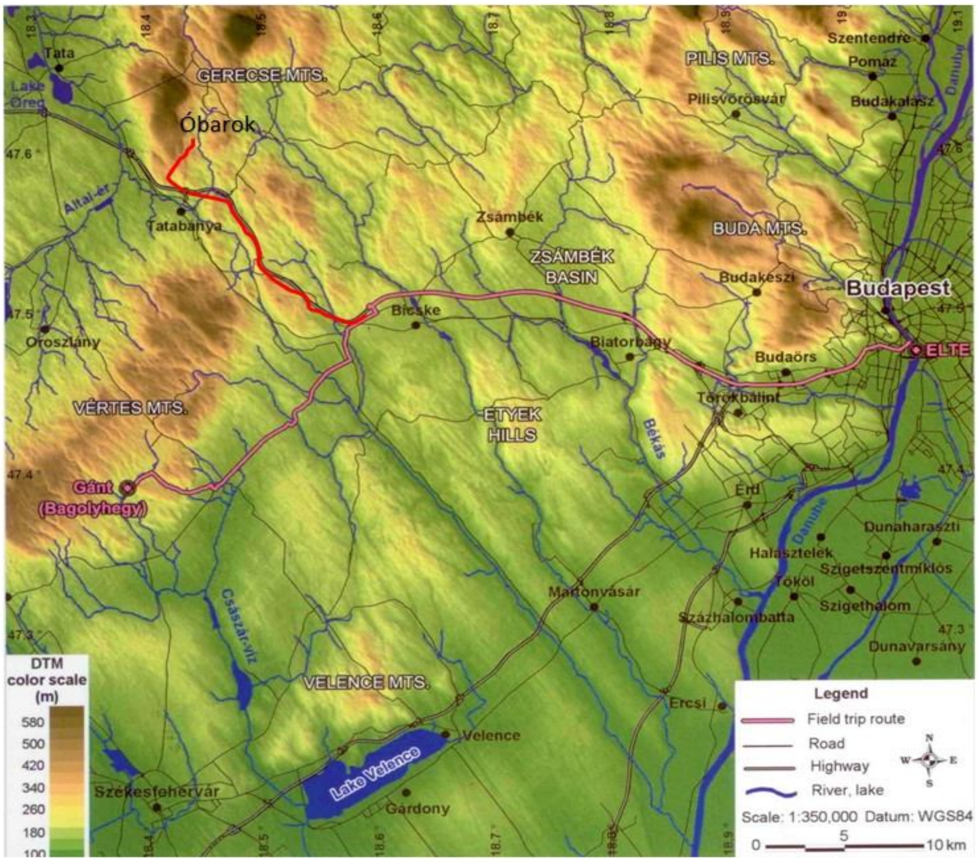


Fig. 2 Topographic map of the area visited by the excursion (Óbarok in the southern extreme of the Gerecse Hills and Gánt on the southeastern margin of the Vértes)

Karst Bauxites in Hungary

Hungary's Transdanubian Range having been part of the Alpine Edifice, in Mesozoic-Tertiary times, shared the history of the Eastern Alps. Major events of the Eoalpine deformation including folding, faulting, uplift and subsidence, affected also the TR, though not exactly the same way (eg. bauxitiferous unconformities with commercial-grade reserves, even though almost exactly coeval with those in the NCA, are more abundant in the TR than in the NCA). The TR is famous of its Cretaceous-Early Tertiary bauxites, which for a long time have been considered among the most important mineral resources of Hungary. They all belong to the group of karst bauxites and occur at major regional unconformities of Albian, Turonian/Senonian early Eocene and early Oligocene age. All four bauxite events have traditionally been considered as having been introduced by (tectonically controlled) uplift and followed, likewise by tectonically controlled subsidence and the concomitant relative sea-level rise.

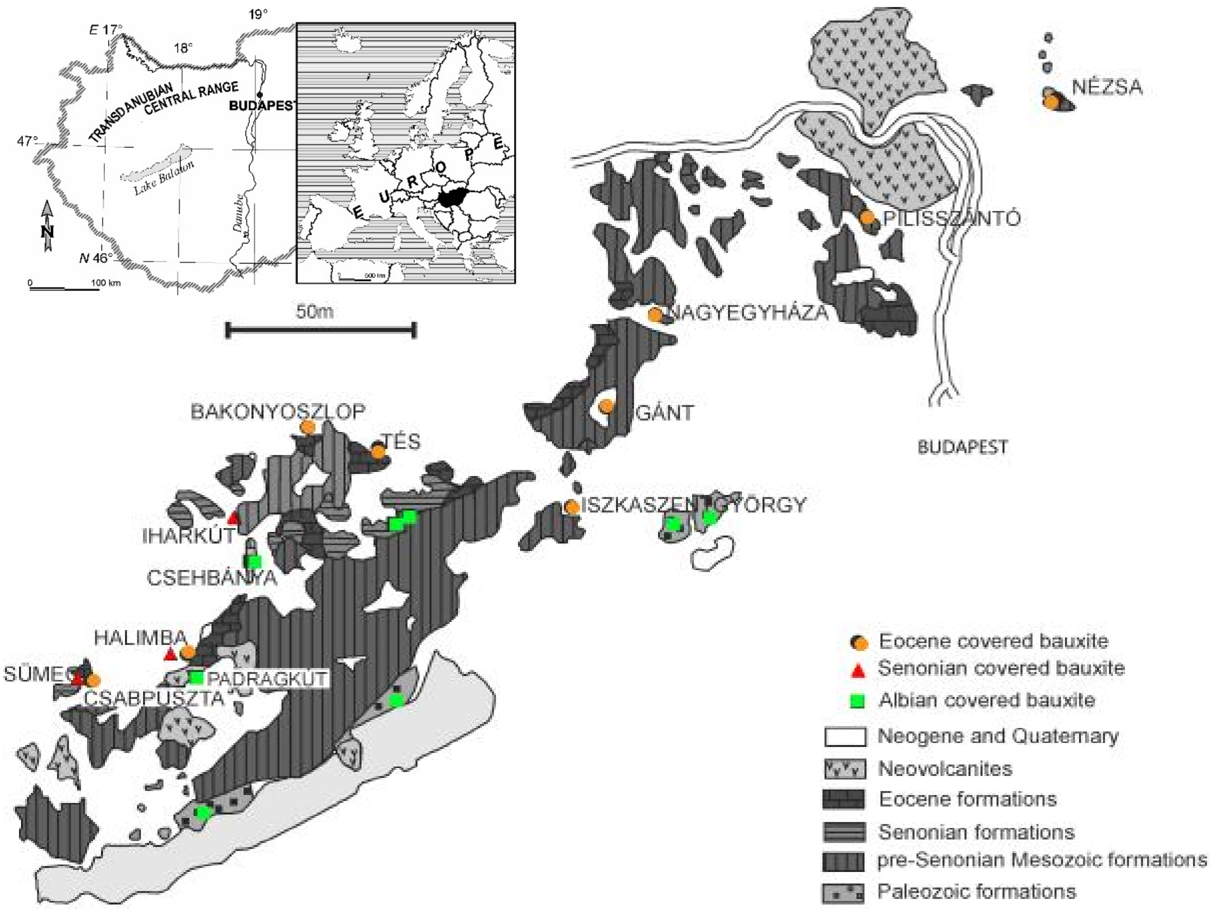


Fig. 3 Geological sketch map of the Transdanubian Range

As a result of subaerial exposure a typical karstic surface relief and also a karstic micro- and macroporosity was created and partially or completely filled by bauxites. The transgressive sequences overlying the individual bauxite horizons are carbonatic, their lithofacies reflecting the antecedent palaeotopography. Bauxites, their bedrocks and the covering limestones have been studied in detail by generations of geologists, mainly form the stratigraphical, sedimentological and economic geological points of view (Vadász 1951, Balkay 1966 Bárdossy 1961, Szantner & Szabó 1970, Szőts 1953,). To correlate bauxites with the structural evolution of the Transdanubian Central Range was attempted by Vadász 1951, Dudich & Komlóssy 1969, Szantner et al 1986. More recently, based on an integrated study of bauxites, their associated bedrocks and the early diagenetic features of their cover Mindszenty et al. 1994 and Mindszenty et al 2000 attempted to incroporate bauxites into the currently available paleogeodyanamic reconstructions. They concluded that the observed distribution of bauxites in the TR is in accordance with the *foreland-type deformation* controlling Cretaceous and partly also Eocene deformation of the area, put forward by Tari 1994. In this context, Cretaceous bauxites can be considered as weathering products formed and partly redeposited on the apex and the flanks of a migrating gentle forebulge, in the Senonian already involved in thrusting. In the Eocene the geodynamic scenario seems to have changed inasmuch as the morphology of the deposits shows the imprints of large-scale strike-slip movements, probably related to the beginnings of the „escape" of the Transdanubian Range from its original East-Alpine position (Kázmér & Kovács 1985).

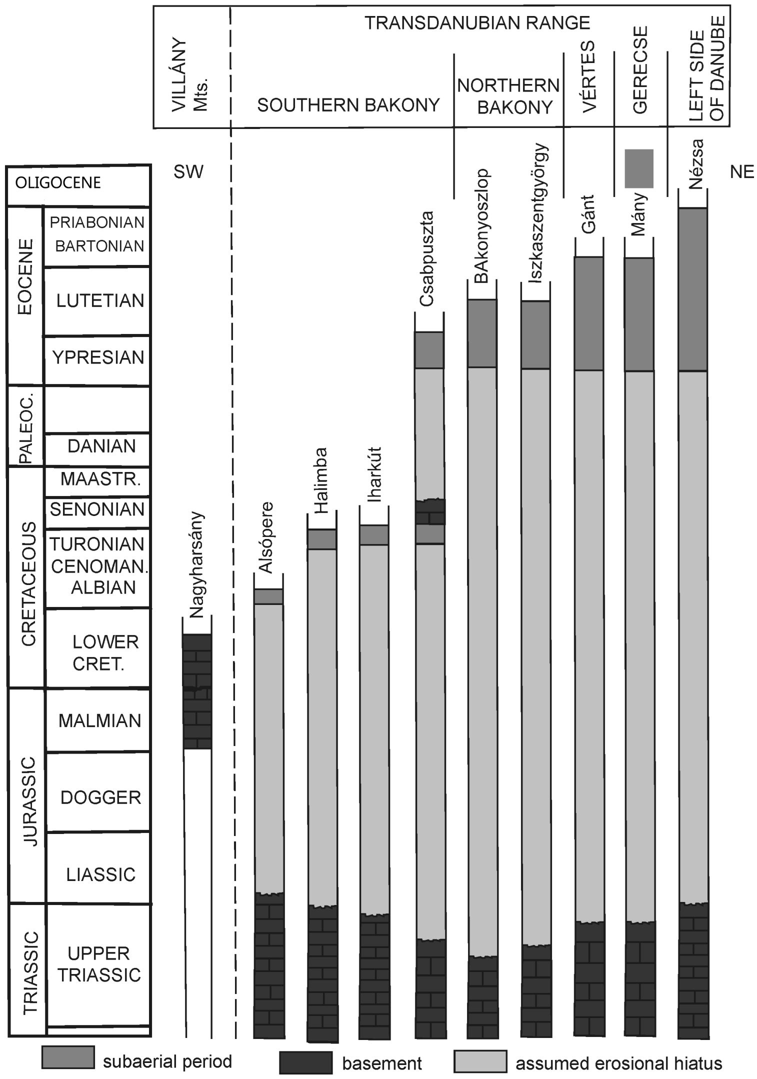


Fig. 4 Stratigraphic position of karst bauxites occurring at major regional unconformities in the Transdanubian Central Range and in South Hungary (Villány) (Stratigraphy of the Eocene coverbeds after Nagymarosy & Báldi-Beke 1988)

Lithofacies and micromineralogy of the three bauxite horizons are different. Albian and Senonian bauxites, though both displaying distinct oolitic-pisolitic textures are different in terms of porosity (Albian: 6%, Senonian: 25 to 28%). Eocene bauxites are either pelitomorphic or intraclastic to gravelly with pesudo-ooids only. Their micromineralogy substantially changes with time: in the scarce (0.01%)

acid-insoluble residue of Albian bauxites titanite, amphibole, kyanite and some calc-alkaline igneous rock-fragments were detected, whereas in the Senonian ones only the ultrastables (zircon, rutile, tourmaline), some calc-alkaline igneous and very few anchimetamorphic rock-fragments could be identified. Eocen bauxites are an order of magnitude richer in detrital minerals, in addition to the ultrastables they abound in higher metamorphic minerals and rock fragments (garnet, staurolithe, sillimanite, kyanite) euhedral volcanogenic zircon and ilmenite grains and even some volcanic rock fragments of trachytic texture were identified in them. Zircon grains were fission-track dated as Eocene by Dunkl (1992) pointing to contemporaneous volcanic activity contributing to the pre-bauxitic material. Detailed micromineralogical study combined with U-Pb geochronology is underway by Kelemen et al 2020 with the aim of refining the stratigraphic position of bauxite horizons in the TR.

GÁNT, THE FIRST-EVER COMMERICAL-GRADE BAUXITE DEPOSIT DISCOVERED IN „POST-WORLD-WAR" HUNGARY IN 1924

The „cradle" of Hungarian bauxite mining, the Gánt deposit, was discovered by a Transylvanian mining engineer J.Balás in 1924. The discovery was one of the results of the desperate effort of Hungarian geology after World War I, to disclose new mineral resources within the country which as a result of the peace treaty of Trianon, has lost two thirds of its territory including all its former prosperous mining districts.

Mining activity began here in 1926 and was followed soon by the first scientific descriptions of bauxite (Telegdi Roth 1927, Vadász 1927, Pobozsny 1928, Gedeon 1932 and Dittler 1931). Ever since then the locality has attracted many mineralogists, geochemists, paleontologists and structural geologists to study the peculiarities of both bauxite and its cover (Szőts 1938, 1953, 1956, Kiss 1953, Strausz 1962, 1964, Kopek et al. 1965, Bignot et al 1985, Deák 1967, Vörös 1969, Bárdossy 1961, 1980, Szantner& Szabó 1970, Mihály 1975, Farkas et al. 1982, Mihály & Vincze 1984 and German-Heins 1994). By 1936 with 500 000 tons pro year Hungary became the third-largest bauxite producer of the world. Additional deposits were discovered both around Gánt and at other localities of the Transdanubian Range as a result of which production has steadily increased until after 1989 when it totalled to almost 3 million tons pro year (from open-cast and underground mines). In Gánt exploitation peaked in the mid '50ies with 477 000 tons pro year from five large open-pits. Since then it has gradually declined until the mid '80ies when it was finally closed. The Bagoly-hegy open pit, where J.Balas started the exploration in 1924 was converted into a geological park in the early '90ies by the Bakony Bauxite Mines.

General Geology

The occurrence is situated at the SE foothills of the Vértes Hills which is of an asymmetric monoclinal structure sligthly tilted to the NW and dissected by two major sets of faults (SSW-NNE and NNW-SSE). The bulk of the hilly range is built up of Triassic rocks (Ladinian to Carnian dolomites and marls, Norian dolomites and Rhaetian limestones) Younger Mesozoic members are known from scattered outcrops and boreholes only, from along the SW margins of the area. The Tertiary cover is discontinuously exposed on the surface along both the western and the eastern foothills. Bauxite deposits are known from the eastern part only, where the Eocene succession reflects a stepwise transgression, beginning in the latest Middle Eocene („Marinesian" or „Bartonian" more orless equivalent to P 12/14 and NP 16/17 respectively, according to Bignot et al 1985 and Pálfalvi 2007).

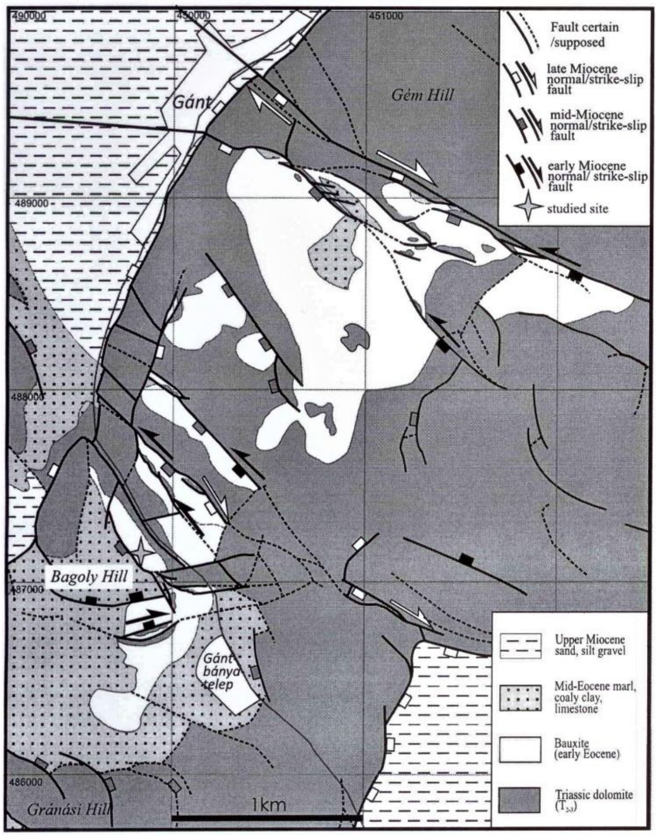


Fig. 5 Structural geological map of Gánt and its surroundings (by courtesy of Fodor, L.)

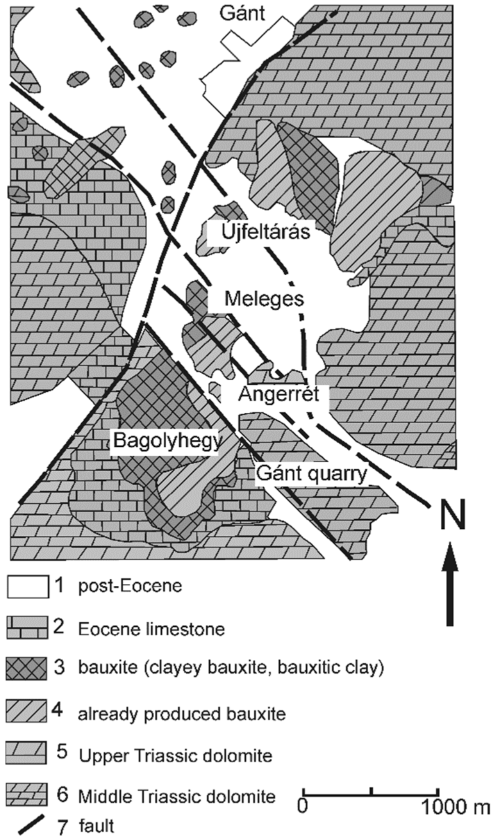


Fig. 6 Major open-pits exposing the bauxite in the Gánt area as in 1969 (Bauxite Prospecting Co.1969)

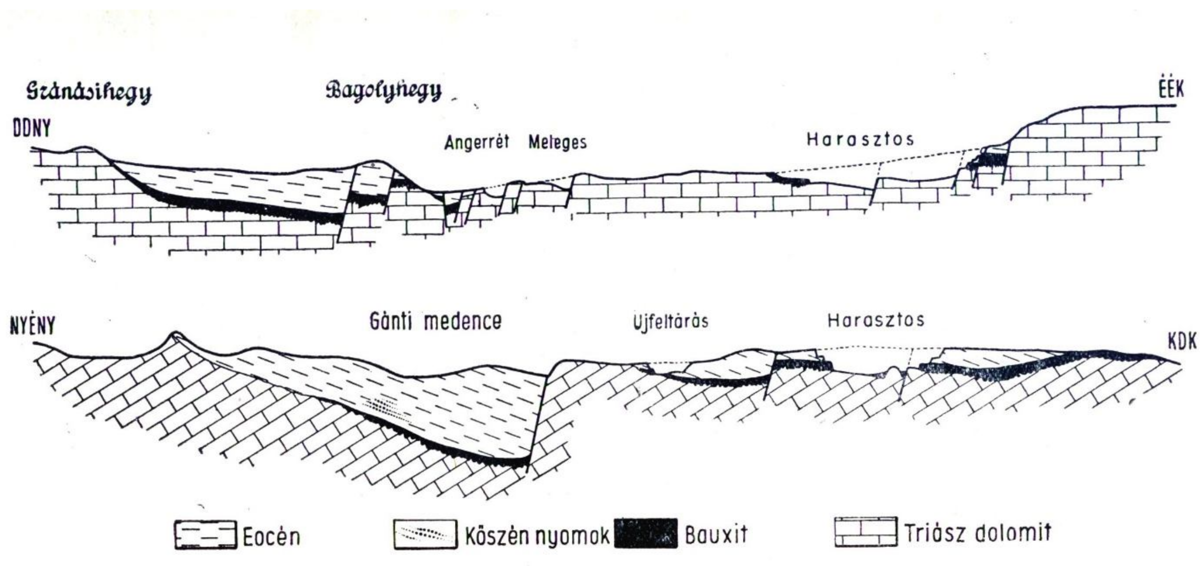


Fig. 7 Sketch-profiles across the Gánt bauxite occurrence (original by Vadász 1951)

The bauxite occurs at a major regional unconformity between Late Triassic and late Middle Eocene strata and is generally considered as of Paleocene-Eocene age. It fills a shallow karst relief formed as a result of long-lasting subaerial exposure. Lateral size of individual deposits is several hundreds of meters, the thickness of the bauxite is moderate (10 to 15 meters). Major bauxite minerals are: boehmite, goethite, hematite, kaolinite and anatase accompanied by minor chlorite (chamosite). There are two lithological types recognized at this locality: pelitomorphic and conglomeratic. Both are of medium-quality with the pebbles being of higher grade (Al_2O_3 31,6%, SiO_2 1,5%) while the muddy, pelitomorphic material, though richer in alumina (Al_2O_3 46,9%) is richer also in SiO_2 (11,3%). According to Bárdossy (1961) the average grade of the ore in the Gánt area (all lithotypes considered) was Al2O3 50,0% and SiO2 16,0%). Both lithotypes abound in textures suggesting repeated mobilization and reprecipitation of iron oxide – a sign of accumulation and early diagenesis in a semi-vadose to semi-phreatic environment, probably close to the paleo-groundwater table.

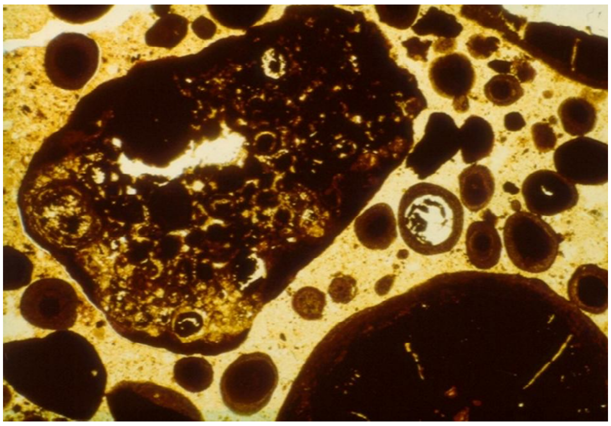


Fig. 8 Thin section photomicrograph of gravelly bauxite from the Bagolyhegy deposit. Plain light (short side of the photo is ~1 mm)

Fig. 9 Field-sketch of gravelly bauxite from the Gánt-Bagolyhegy open-pit by Szarka, A. in Mindszenty et al. 2010 (pencil for scale)

The predominantly pale red to yellowish coloured bauxite forms an extensive 10 to 12 m thick blanket over the karstified surface of the Triassic bedrock. The amplitude of the karstic mezo- relief is a few meters. The bauxite displays outcrop-scale stratification with the moderately to poorly sorted conglomerate layers forming irregular intercalations in the muddy „matrix". The conglomerate may be matrix-supported or clast supported, the clasts are rounded to subrounded and of 0,5 to2,0 cm size on the average, occasionally with 10 to 20 cm size boulders, as well.

As shown by its sedimentary characters, the Gánt bauxite is of a rather peculiar depositional type. Unlike most karst bauxite deposits it is not simply the result of parautochthonous transport of the polygenetic weathering product on the karstic terrain. It displays the signs of true allochthony and - as shown by its coarse, chaotically organized conglomeratic textures – it was apparently deposited on a shallow karst terrain from episodic mudflows/debris flows probably triggered by synsedimentary faulting. The once continuous extensive bauxite blanket is dissected by numerous postdepositional mostly Late Tertiary) faults, some of them clearly visible in the visited outcrop.

Gánt Bagolyhegy abandoned open-pit

Though vegetation has already partly overgrown the walls of the abandoned quarry, it is still spectacular inasmuch as all the important characteristics of this peculiar deposit can be studied in details.

The visited part is an elongate pit roughly perpendicular to the main road connecting Gánt-bányatelep with the village of Gánt. Boulders of the altered bedrock and the most important members of the transgressive cover sequence crop out either from below the vestiges of bauxite left over by mining or in the quarry-walls. Post-depositional faulting is obvious on the northern side of the quarry (right below the building of the Mining Museum at the northern extreme of the quarry) and also at the far end of the quarry towards the east

General view of the quarry and tectonic elements visible on the quarry wall.

The rocky cliff below the Mining Museum is a steep fault plane with oblique striae on its surface suggesting that movement along the plane was mainly lateral with only a slight normal component. A fine example of a meter-scale relay-ramp transferring the movement from one of the en-echelon faults to the other is clearly seen when looking towards the Museum. For more information see Fodor (2007) and Budai & Fodor (2008).

Close-up view of the faults plane permits the observation of the fault-breccia along which worn, powdered dolomite clasts are already partly missing while the breccia is strongly cemented by calcite displaying a kind of a boxwork texture.

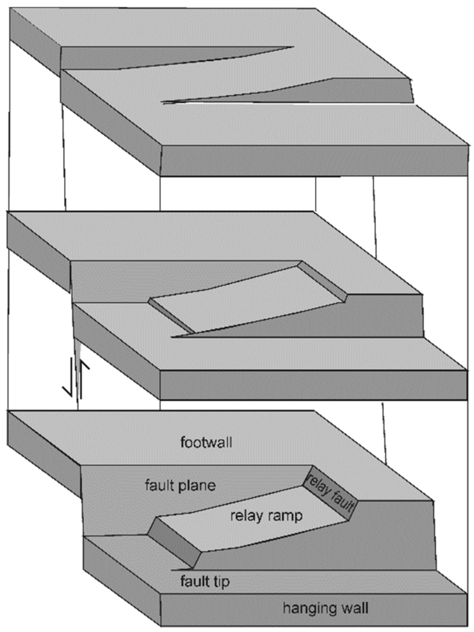


Fig. 10 Development of a relay-ramp (according to Peacock & Sanderson 1994)

Altered bedrock cropping out from below the bauxite

Between bauxite and bedrock there is a several cms thick iron-rich crust consisting of hematite pseudomorphs after 0.5 to 3 mm size euhedral pyrite. The boundary between crust and the underlying dolomite is sometimes sharp sometimes diffuse in the latter case with a transitional zone consisting of powdered dolomite, cemented by hematite and calcite by which dolomite has completely lost its original identity. The thickness of the Fe-„metasomatized" altered zone may reach several tens of cms. As compared to the unaltered dolomite the crust is clearly enriched in Mn, Cu, Zn, Mo and Co and also in As. German-Heins (1994) proposed that the originally pyritic crust was formed when shortly after the deposition of the bauxite tectonically controlled subsidence resulted in relative sea-level rise and as the first sign of transgression the bottom of the bauxite deposit was flooded from below by saline pore-waters. Anaerobic decay of organic matter (mainly the vestiges of terrestrial vegetation trapped underneath the bauxitic mud-flow) led to microbially mediated early diagenetic sulphate reduction. Sulphur has readily combined with the not yet stable Fe-hydroxide phases of the bauxite thus leading to the precipitation of pyrite at the bottom of the deposit. That the precipitation of pyrite has in fact „utilized" Fe from the bauxite is shown by the pale deferrificated bauxite halo around the encrusted bedrock-cliffs protruding from below the bauxite.

Fig. 11 Dolomite, heavily encrusted by iron oxide

Pyrite could have been oxidized when the deposit became in contact with oxidizing meteoric waters again. This could have happened either during any one of the oscillatory phases of the Eocene transgression itself, or later on during telogenesis of the Gánt bauxite deposit.

Coal-seam in the cover of the bauxite

On the dissected karst terrain transgression began with the slow upraisal of the groundwater table. Depending on the meso-topography and the relative elevation of the bauxite-covered terrain this has resulted in a mosaic of various lithofacies in the immediate cover, including sediments deposited in smaller or larger freshwater ponds and/or marshes. On transgression the normal sequence would be fresh-water pond → freshwater-marsh → brackish-marsh → brackish lagoon → restricted marine lagoon → open marine lagoon, however, as a result of the oscillating transgression these facies may also repeatedly reappear one above the other.

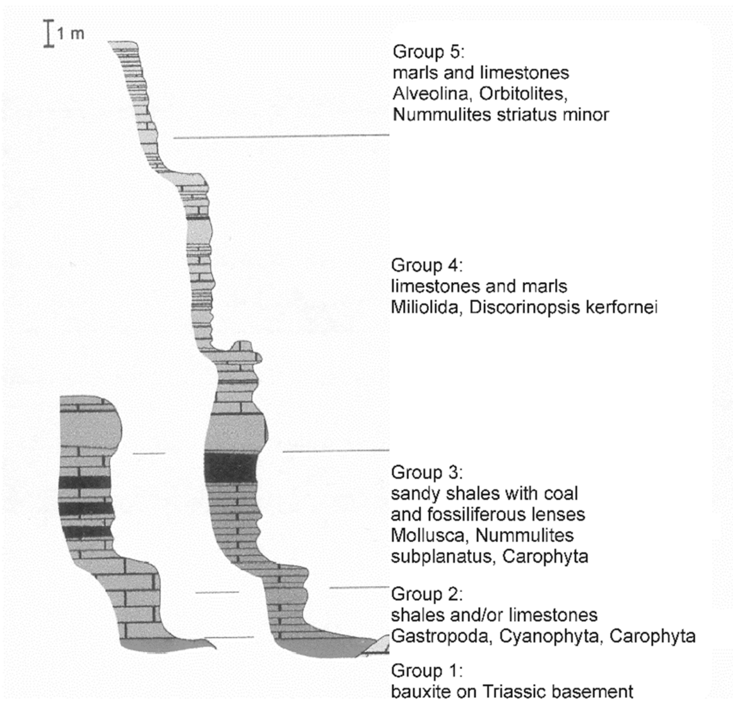


Fig. 12 Transgressive cover-sequence from above the Gánt bauxite

Sometimes thin coal-seams also occur above the underlying (not always visible) sediments of the fresh-water pond. Coal-rank of the exposed seams is always „lignite". As a result of recent weathering in the outcrop they are full of tiny little gypsum crystals formed on interaction with downward percolating late or even actual meteoric waters which picked up their Ca-content while in contact with the overlying limestone.

Characean-rich fresh-water limestone – blue-hole on top of the Gánt bauxite?

Characean-bearing fresh-water limestone occurs in the form of large erratic blocks at the bottom of the quarry. Though they are not in situ, in the present abandoned quarry they are the only proofs of the purely carbonatic fresh-water pond established on top of the bauxite at the beginnings of the Eocene transgression. Higher up in the succession there are also calcareous marls with similar fresh-water biota, showing that as groundwater continued to rise the influx of clays washed in from slightly higher elevated, not yet soaked parts of the karst terrain was also possible. Microfauna and flora of the Bagolyhegy cover-sequence were studied in detail by Bignot et al (1985) and by Carannante et al (1994). Carannante et al. put forward that the trajectory of the Gánt transgression from fresh-water to brackish then schizohaline (without intervening desiccation events) and finally marine would be comparable with the depositional sequence described by Rasmussen and Neumann (1988) from the Bahamas: They suggested that this kind of transgression is a result of the antecedent karst topography. It is similar to what we see in the case of the inland blue-holes of the Bahamas and it should be called „internal" transgression as opposed to the conventional „Waltherian" overland transgression.

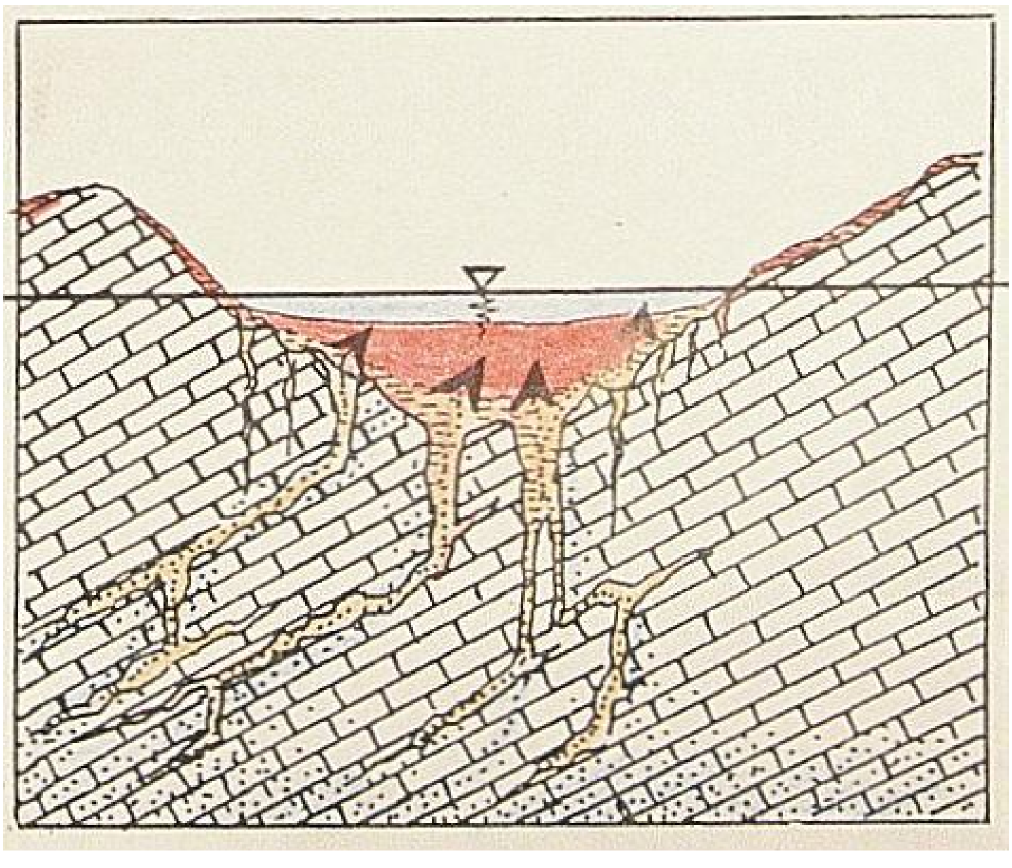


Fig. 13 Cartoon showing the idea of the „internal" transgression (sensu Carannante et al 1994)

The bauxite

Pelitomorphic bauxite

Exposed in the quarry-wall light red bauxitic mudstone, called pelitomorphic bauxite can be seen. Scattered in the muddy hematitic matrix there are small (2 to 3 mm) yellowish-brown (7,5YR5/8, 7,5YR4/6) goethitic grains – intraclasts or small nodules. They are supposed to be fragments of pedofeatures formed in the ferrallitic soil before landscape stability was ended and the material became involved in large scale resedimentation by the afore-mentioned mudflows/debrisflows.

Bauxitic conglomerate

Cliffs made up by coarse bauxitic grainstone crop out from below the scree. The grains look like pisoids, they are yellowish-red, more or less spherical and have a yellowish porous coating. When hit and crushed into two with a hammer it turns out that they are not pisoids but intraclasts mainly reddish in colour suggesting that they may be redeposited pedogenic nodules or soil-fragments. These conglomeratic layers are supposed to have been produced by large-scale soil erosion and resedimentation related to climate-deterioration probably coincident with synsedimentary tectonic events (Mindszenty et al 1989)

Paleosoil profile with burial gleying on top of the bauxite

Right underneath the Eocene cover the top of the bauxite displays a strange colour-alteration. Pale whitish to grayish, vertical to subvertical mottles abound in the uppermost 1 m of the deposit. They are considered to be drab-coloured root-traces, remnants of the last soil profile apparently developed on the bauxitic substratum still under moderately well-drained conditions (root-traces are vertical to subvertical!). Organic matter of this paleosoil was, however destroyed under anaerobic conditions when groundwater table began to rise and moderate drainage changed for hydromorphy resulting in burial gleying in this top-layer of the bauxite.

Tectonics

Fault plane (partly synsedimentary, partly post-mid-Eocene)

Mining activity exposed a major east-west trending normal fault at the far end of the quarry. The exposed length of the fault is about 300 meters. Dissected by the fault plane the karst relief underlying the bauxite is superbly exposed in this outcrop. Based on the numerous fault striae and associated Riedel-faults, displacement along the major fault was right-lateral combined with a normal component of about 5 to 6 meters (Fodor et al 2005). The faulted zone was strongly brecciated/powdered, the estimated thickness of the fault-breccia being several meters or so. In accordance with its increased porosity the fault zone was subject to intense cementation mainly by calcite. Subsequent weathering resulted in peculiar boxwork textures best seen on smaller or larger bedrock-blocks protruding from below the bauxite in front of the fault-plane. Powderization and cementation of the bedrock mainly by calcite and iron oxide is characteristic of this fault-plane related variety of the Triassic dolomite.

Fig. 14 View of the major boundary fault of the Bagolyhegy open-pit

Sedimentary structures in gravelly bauxite (chaotic texture, soft-sediment deformation)

On the upthrown block of the fault-plane the bauxite displays clear signs of soft-sediment deformation: yellowish conglomerate layers intercalated in the pale-red bauxitic mudstone are bent downwards suggesting that displacement along the fault began while the bauxite was still unconsolidated. That the fault was reactivated after the deposition of the coverbeds, as well, is shown by the displacement of the Eocene sequence visible on the western wall of the quarry.

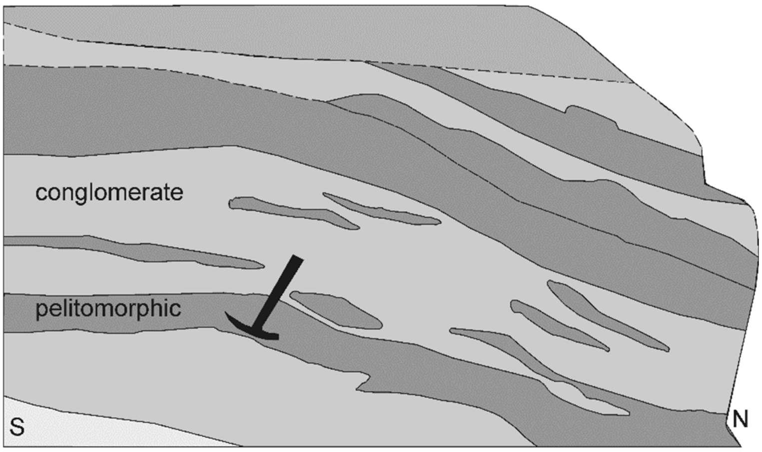


Fig. 15 Alternation of conglomeratic and pelitomorphic bauxite on top of the major boundary- fault in the Bagolyhegy open-pit (field-sketch). Note that the layers are all bent towards the downthrown block

Overview of the Gant bauxite deposit from the top level of the abandoned Bagolyhegy open-pit

Fig. 16 To the right: major synsedimentary fault rejuvenated also in post-Eocene times. To the left: on the downthrown block, karstified dolomite cliffs crop out from below remnants of the bauxite.

Óbarok – penultimate large-scale bauxite mine in Hungary

The Oligocene bauxite of Óbarok

Abandoned quarry exposing the remnants of the Óbarok-XI. deposit

History

Bauxite was discovered in the southeastern forelands of the *Gerecse Hills* in 1928 by a reconnaissance survey launched to reveal the mineral resources potential of this area. In addition to bauxite also other mineral commodities like coal and eventual raw-materials for the cement-industry) were searched for. Open-cast mining started on the near-surface bauxite deposits of Újbarok and Óbarok in 1943, when – towards the end of the 2nd World War the production of the nearby Gánt deposit was already insufficient to meet the then rapidly increasing bauxite-demand of the market. By the end of the war, however, the Óbarok open pits became all abandoned because the front-line has reached the area. Interest in the Óbarok bauxite began to grow again, after a long pause, only in the late '90ies. That was a period when undergoround mining acitivities had to be uspended because of their deteriorating effect on the karst-water-reservoir of the TR. Pressed by the need of near-surface reserves, the Bakony Bauxite Mines have started a detailed exploration campaign also in this area. After the first promising results, by the mid '90ies they have completed also the proving drilling stage and in 1997 the quarry exposing the Óbarok-XI. deposit was opened up. Production continued until after 2002 when, facing overall economic problems, the mining company had to close down the operation permanently. The former open-pit is currently subject to refilling with inert construction-waste. Total amount of bauxite exploited from the Óbarok XI depos between 1997 and 2002 was 515 000 tons

Fig. 17 Panoramic view of the open-pit exposing the Obarok-XI. deposit as in 2002

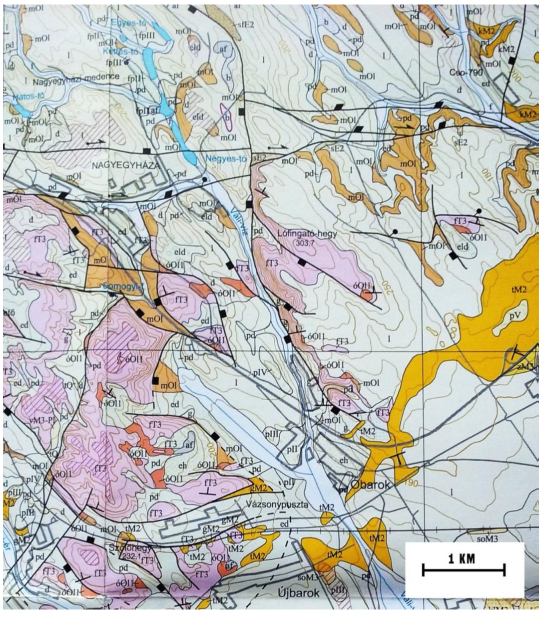


Fig. 18 Geological map of the Óbarok area (Budai and Fodor 2008

Geological framework

Stratigraphy

The village of Óbarok is situated in the northern part of the Transdanubian Range right below the steep NW-SE striking Triassic dolomite escarpment of the Lófingató Hill. The gently descending NE slopes of the Hill are blanketed by 5 to 7 m of Quaternary loess. Underneath the loess, and another 10 m of Oligocene siliciclastics, commercial-grade bauxites rest on the uneven karstic surface of the Triassic dolomite.

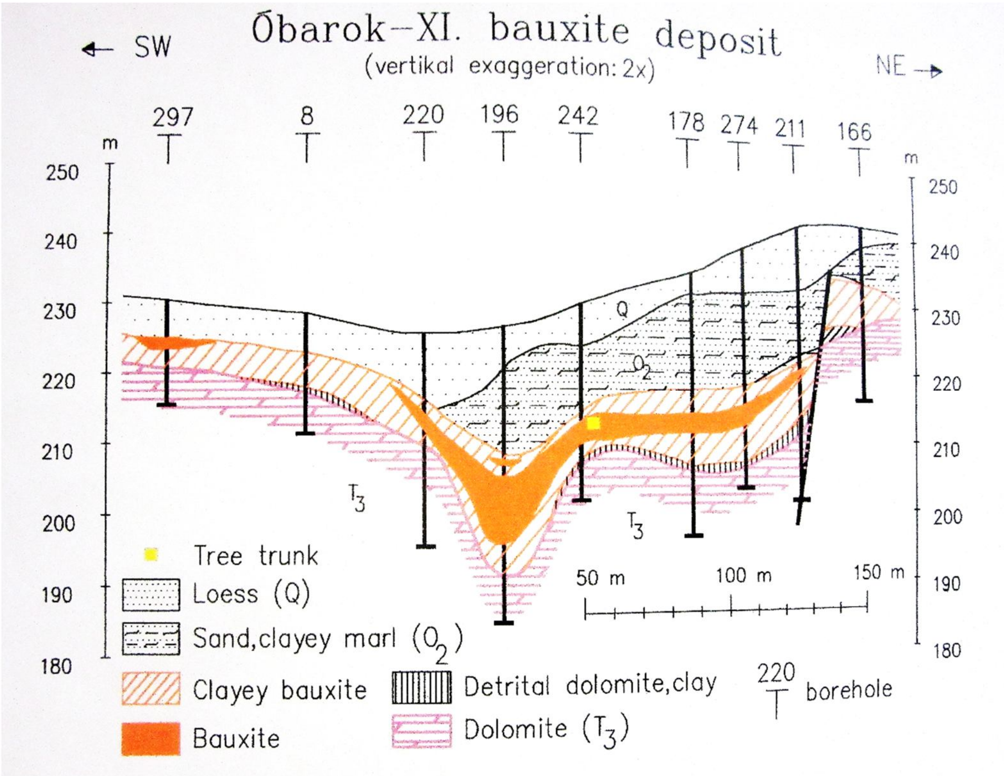


Fig. 19 Geological profile across the Óbarok-XI. bauxite deposit (according to Böröczky T. and Varga G. 1996)

Even though the apparent statigraphic gap between the bedrock and the cover of the bauxite is rather large (Triassic/Oligocene) and all over the Transdanubian Range there are several bauxite deposits the Cretaceous and/or Eocene age of which is stratigraphically well constrained, we have good reason to think that at Óbarok, the actual hiatus was relatively short. Jurassic and early Cretaceous sediments are known in pelagic facies from nearby outcrops suggesting, that they must have been present also in Óbarok and their absence is the result of deep-reaching erosion which took place some time, definitely in post- late-Cretaceous times. Based on the analogue of similar bauxite deposits occurring in in the surrounding basins it has been generally accepted that the subaerial period resulting in bauxite formation and possibly also in partial erosion and redeposition of previously formed (probably Eocene) bauxites could not have been longer here, than incorporating the latest Eocene/early Oligocene.

According to detailed observations on cores of the exploratory boreholes, fragments of Rotaloid foraminifers of Eocene age, were found in the bauxite (Böröczky 1996). This suggests that at least part of the bauxite is undoubtedly the redeposited, eroded remnant of some older (Eocene) bauxite mixed with fragments from the likewise eroded Eocene cover. Thus the accumulation of the Óbarok bauxite we see now, must have clearly postdated the Eocene, so its age is, indeed, *intra-Oligocene* and duration of the apparent stratigraphic gap at any particular place depends entirely on the lateral variations of the intensity/depth of the pre-Oligocene erosion. That the accumulation of bauxite over the karstified dolomite terrain was still an ongoing process in Oligocene times is clearly shown also by an about 0,5 m long, hematitized *Dacrydioxylon* trunk –fragment found in the bauxite during the mining operations and identified by *L.Rákosy* (in: Mindszenty et al. 2002). The oldest remnants of this plant were described from the Oligocene and its closest relatives are living now in Tasmania. The results of fission-track dating of zircon-grains separated from the bauxite and apparently having originated from contemporaneous volcanic sources do not contradict the palaeobotanically based biostratigraphy (Dunkl oral comm.) and U/Pb age-datings currently underway by Kelemen et al. (2020) on the micromineralogical residue of the Óbarok bauxite will hopefully further improve our knowledge regarding its precise stratigraphic position.

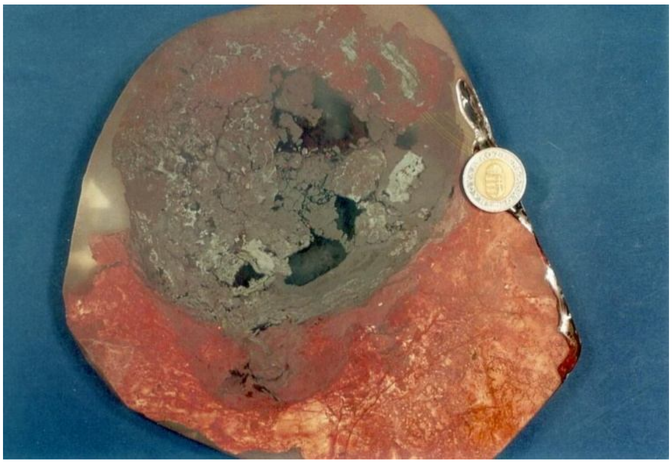


Fig. 20 Cut slab of the haematitized Dacrydioxylon fossil found in the Óbarok bauxite by Rákosy L.in 2002

Palaeoclimatological aspects

The fact that bauxite considered to be the product of *humid tropical weathering* and occurring in *commercial quality and quantity* in the *Oligocene* of this part of Europe, may be of particular importance also for palaeoclimatologists. Climatic effects of the Eocene Oligocen Transition (EOT) have been in the past years very much in the focus of interest of paleoclimatologists (eg. Urban et al. 2010, Hren et al. 2013, Kocsis et al.2014). Latest results of Pound and Saltzmann 2017 suggest, that the response of the continental realm to the generally accepted *global cooling* in Late Eocene – early Oligocene times was rather *mosaic-like*. According to their investigations, during the EOT, decreasing mean annual temperatures were manifested at several places in cooler winter-months only. Summer-temperatures, however, remained quite high (> 25°C) thoroughout. Precipitation – depending heavily on the orogeny-created relief - was at places still high, while at other places (eg. in orographic rain-shadows) decreased considerably. The major change was rather the increase of seasonality. So the Óbarok bauxite can be considered as a testimony for high temperatures, sufficient amount of rains and pronounced seasonality in this particular area of the Circum-Mediterranean Region. Without high-enough temperature and abundant rains the quality of the bauxite should have been deteriorated considerably. But the bauxite is of *high quality* and the only sign of climate change is recorded by its texture. It is often clearly autoclastic/brecciated which may be assigned to periodically intense desiccation. In the rainy seasons torrential rains could have transported and redeposited the broken up pieces of the muddy material locally. Seasonality is reflected also by the structure of the above mentioned plant fossil.

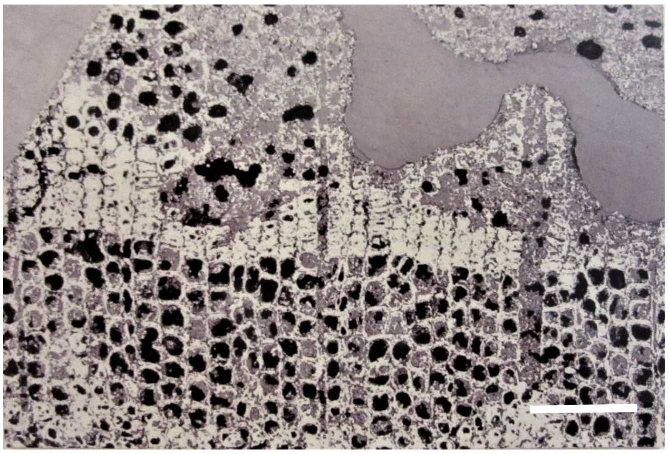


Fig. 21 Haematitized plant-tissue of the Dacrydioxylon fragment. Note the large tracheyds indicative of the rainy season and the flattened ones formed in the dry periods. Reflected light. Scale bar:100 µm (Photo by L.Rákosy)

Burial history

After the long-lasting subaerial period, in late Early Oligocene times also the Óbarok area shared the destiny of the Palaeogene basins of Hungary: it became subject to subsidence and an overall transgression by the sea.-The bauxite became covered by a silty-sandy, clayey, higher up also calcareous (marly), predominantly silicilastic sedimentary succession, occasionally – in the lower parts – with thin, lenticular, coarser grained (gravelly) intercalations. The depositional environment of these strata is supposed to have been a brackish to shallow marine coastal plain (Tari 1994, Budai et al. 2018). Diagenetic features of the bauxite show that well before the actual transgression recorded by the siliciclastic sequence, the bauxite deposit must have been exposed to repeated groundwater-table oscillations. Changing redox conditions resulted in repeated *mobilization and reprecipitation of iron* and also *manganese.* Such changes are evidenced (a) by the dark reddish- to blackish-coloured iron-rich crust at the interface of bauxite and its bedrock; (b) the small iron-oxide-rich plant-remnants and the above mentioned large haematitized tree-trunk, and (3) the abundant rhytmic ironoxide concentrations and deferrification patches in the bauxite. *Manganese,* being more sensitive to redox-changes than iron, could not co-precipitate with haematite but was likely adsorbed on the surface of the previosuly already mineralized ironoxide and clay phases of the bauxite at places resulting in anomalously high MnO_2 concentrations (0,69% on the average) in the Óbarok XI deposit, at places reaching even 5,0%! (Böröczky 1996)

Since the boundary between the Oligocene sequence and the overlying Pleistocene loess is erosional, the local record of the Late Oligocene to Miocene and Pliocene story is missing. All we know from the geology of the wider surroundings is that during the opening of the Neogene Pannonian Basin, until after the late Mid Miocene the Óbarok area - as part of a relative basement- „high" - was in marginal position. It became overridden by the sea only in late Miocene times. About 8 My ago substantial uplift and erosion of the wholeTransdanubian Range began and affected also this part of the Gerecse Hills.

The erosional surface, thus formed is covered by-the often redeposited – loess-blanket we see on the highest parts of the quarry exposing the Óbarok XI. bauxite-body.

Mineralogy, geochemistry, petrography and sedimentology of the bauxite

Mineralogy

Main alumina-minerals (all of submicroscopical size) of the Óbarok bauxite are *gibbsite (*10,9%) and *boehmite* (49%). Of the iron minerals *haematite* is predominant with 10,4%., accompanied by *goethite* (8,2%). SiO2 is bound to *kaolinite* (12,9%). Acccessories are anatase (2.0%), *lithiophorite* (1,8 %), and *crandallite* (1,3%). Silt-size rutile, ilmenite and quartz (all <1 %), occur in the micromineralogical fraction. Silt and sand-size calcite +dolomite (1,5%) are detrital contaminants (Data from Böröczky 1996).

Geochemistry

Based on calculations of the Bakony Bauxite Mines (Böröczky 1996), at the beginnings of the mining operations, the average chemical composition of the measured bauxite reserves of Óbarok, was as follows

Al_2O_3 46,60%	max: 58,46% min: 39,30%	MgO	0,28%
SiO_2 7,0%	max: 12,70 min: 2,96%	MnO_2	0,69%
Fe_2O_3	**17,6%**	$FeCO_3$	0,03%
TiO_2	**3,01%**	C_{org}	0,11%
L.O.I.	**22,63%**	$\sum S$	0,11%
CaO	0,76%	P_2O_5	0,40%

Based on recent analytical data, acquired in the frames of the REEBAUX project, the average REE contents are:

$\sum$REE 600 ppm (average), max: 905 ppm (LREE > HREE, with La and Ce being predominant)
$\sum$REEY 905 ppm (average), max: 953 ppm

The analyses of the major components show that the Óbarok bauxite is of medium grade, originally deposited under vadose (clearly oxidizing) conditions. The relatively high MnO_2, P_2O_5, C^{org} and $\sum S$ contents even without macroscopically visible pervasive removal of ironoxide compounds, however, call the attention to possible effects of unusual redox processes during diagenesis (see later)

Petrography

Based on field-observations and detailed optical microscopic investigations Böröczky (1996) distinguished four major lithological types:

(1) Bauxitic mudstone (A)

(A) Red to yellowish red (10R5/8 to. 2.5YR5/8) pelitomorphic to, microgranular matrix at places having a sepic fabric and pale-coloured (5YR8/2) deferrification patches. Coarse-grained (500 µm to cm-size) textural elements embedded in this matrix are: intraclasts and scattered bauxite-pebbles. Some times the matrix is crosscut by an irregular network of fine, ironoxide-rich fissures. When this lithology occurs close to the bottom of the deposit it is often rich in silt -size non-bauxitic extraclasts (quartz, quartzite, torumaline and other silicate-fragments). This lithotype is supposed to have been deposited from a dense, slowly moving slurry.

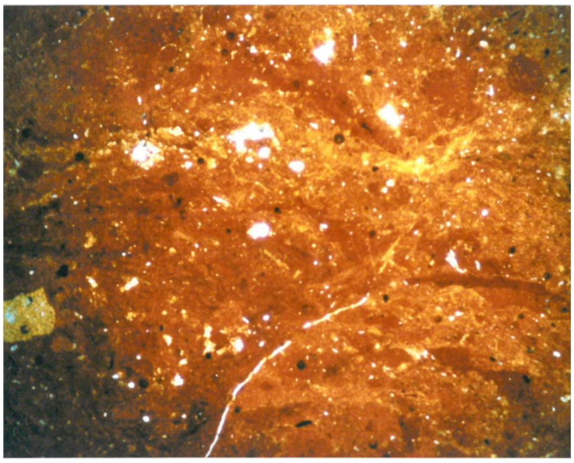


Fig. 22 Photomictograph of bauxitic mudstone (Type „A") with scattered silt-size silicate extraclasts (borehole Ob-292) Plain light, 40x (Photo: Böröczky T.)

(2) Bauxitic mudstone (B)

This is the most abundant lithotype of the Óbarok bauxite. Medium- to dark-red (5YR7/6 to 7,5YR7/6), pelitomorhic matrix with likewise red, iron-rich whisps/shreds and veinlets and hard, sometimes of 4 to 5 cm diameter angular to subangular bauxite clasts and bauxite pebbles in some of them with well-developed ooids. Based on the size of the pebbles this lithoptype is supposed to have been deposited from some higher-energy medium (torrents?). The oolithic character of some of the hard, iron-rich pebbles suggests that they could be eroded remnants of some older bauxites.

(3) Bauxitic wackestone/packstone

Dark red (10R3/6) strongly oxidized pelitomorhic matrix with plenty of 50 µm to even 2 cm size varicoloured (10YR, 10R4/6 to 10R3/6 or some times opaque) mostly pelitomorphic bauxite clasts. Smaller clasts are angular to subangular while the larger ones are rounded. They may be organized into mm-thick irregula/wavy micro- laminae. Occasional grainsize-gradation within the laminae suggests deposition from some medium- to high energy waterflow. Silt-size, non--bauxitic extraclasts (quartz, quartzite, tourmaline etc.) are abundant within the bauxite-clasts but scarce in the matrix It was this lithotype from the matrix of which where the fragments of Eocene fossils were described from (mentioned under „Stratigraphy" above).

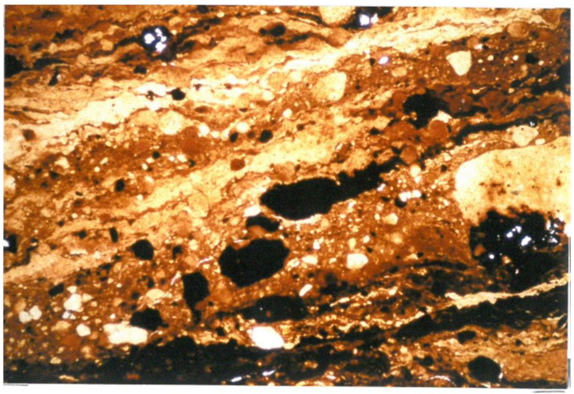


Fig. 23 Photomicrograph of laminated bauxitic wackestone/packstone with iron-rich bauxite micropebbles and non-bauxitic extraclasts (borehole Ob-292) Plain light, 40x (Photo: Böröczky T.)

(4) (Pseudo) brecciated bauxite

Mudstone-type reddish to varicoloured (10R4/8, 10R4/4, 10R3/6, 5Y+5/8, 5Y37/4) bauxite, criss-crossed by a dense irregular network of ironrich (10R3/6, 10R3/2) veinlets (or fissures) resulting in a breccia-like texture.

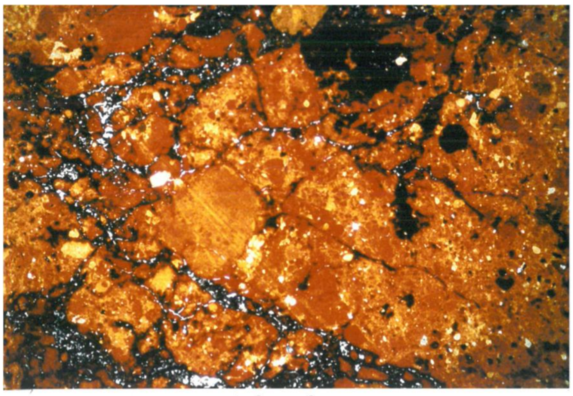


Fig. 24 Pseudobrecciated bauxite (borehole Ob-277) Plain light, 40x

Vertical distribution of the above four lithological types suggests temporal changes in the composition of the material transported to the exposed karst terrain (Photo: Böröczky T.)

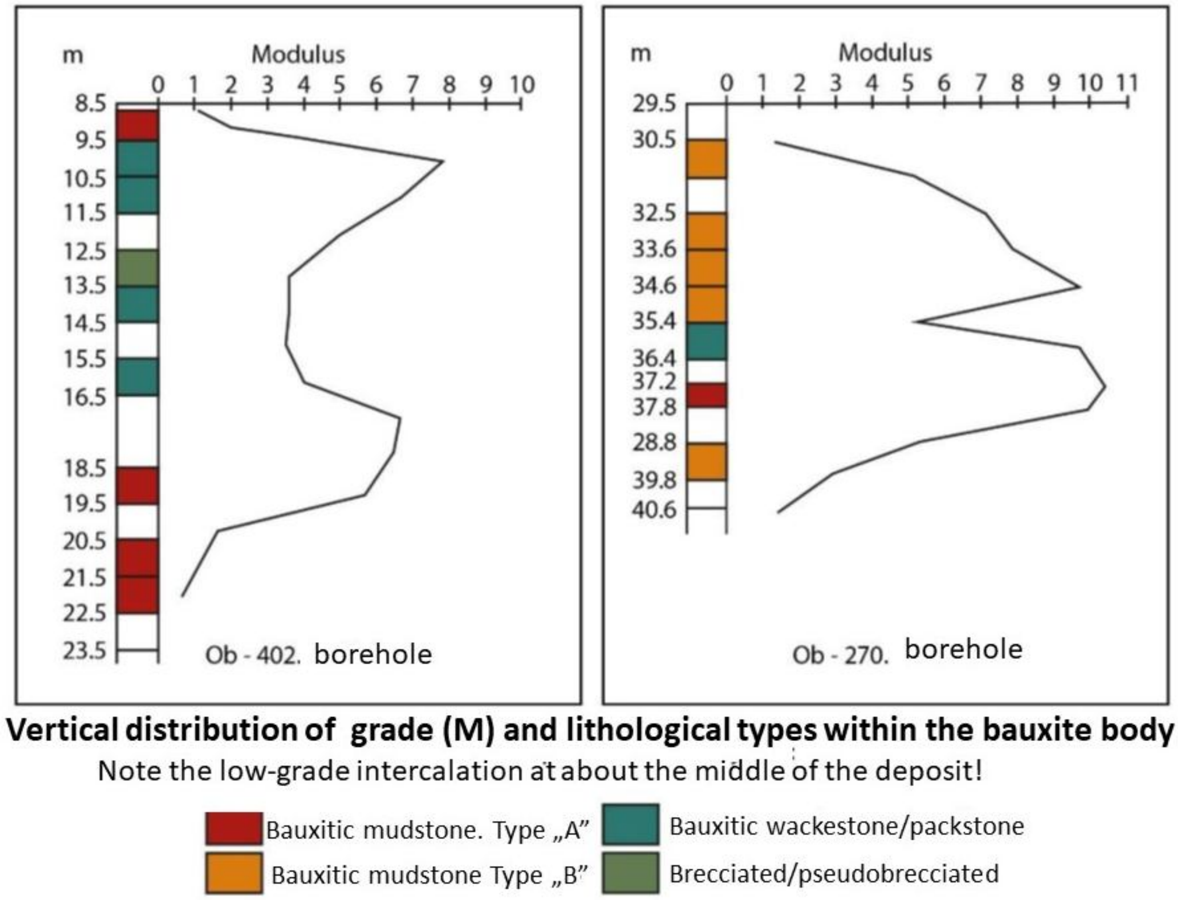


Fig. 25 Vertical distribution of lithological types within the Óbarok-XI. bauxite deposit (Pauletti-Bordy D. 2016. based on Böröczky T.1996)

Sedimentology and Diagenesis

Petrographical analysis and field observations (clastic textures, abundant bauxite-clasts and pebbles) show that the Óbarok bauxite deposit must have received considerable contribution from older, most probably Eocene bauxites, which fell victim to erosion in the surroundings at a time when the Óbarok bauxite was not yet covered. The matrix of these bauxites has desintegrated so it arrived as a bauxitic mud while their more consolidated parts were transported as coarser-grained clasts. The overall red color of the bauxite suggests that the *depositional environment* was, indeed, vadose i.e.oxidizing inidcating that at the beginning of bauxite deposition the karst-surface was still above the karst-water-table). However, the observed abundant iron-mobilization and reprecipitation phenomena, including the iron-rich crust at the bauxite/bedrock contact and the occurrence of the haematitized tree-trunk embedded in the red bauxite, and also the anomalous MnO2-contect of the ore are all indications of some not yet fully understood sequence of redox-processes having affected the distribution of redox-sensitive elements (Fe and Mn) in the bauxite.

We know from Berner (1980) and many others, that mobilization of Fe (and Mn) in the sedimentary environment takes place usually when redox conditions change from oxidizing to reducing. The *vadose*, well-drained (oxidizing) *depositional environment* is characterized by unsaturated pore-spaces and quick destruction of organic matter mixed with the sediment. *Diagenesis*, beginning with incipient burial, brings about a substantial hydrological change: pore-spaces become saturated by groundwater, This results in a *phreatic environment* which –depending on the presence of organic matter, sooner or later will change for *reducing*. Redox sensitive elements when not yet properly mineralized (eg. amorphous Fe^{3+-}oxide phases or ferrihydrite as opposed to well-crystallized, stable haematite) would be mobilized and released in divalent form into the pore-water. Depending on the presence or absence of other ionic species they may reprecipitate eg. as syderite (FeCO3) or pyrite (FeS_2),- the latter only when also S is present. Siderite is generally a sign of the pore-waters being of meteoric origin, while pyrite froms from saline porewaters of marine or brackish origin. On transgression the normal sequence of diagenetic processes in the buried sediment (in our case in the bauxite) would be first the destruction of unstable mineral phases containing redox-sensitive elements ($Fe^{3+,}$ $Mn^{4+),}$ then the formation of siderite and – as porewater chemistry changes – sooner or later pyrite. Mn reduced to Mn^{2+} would be simply leached out, because to precipitate either rhodochrozite $Mn^{2+}CO_3$ or alabandite (MnS) requires more strongly reducing conditions and different ionactivities than those normally characterizing early diagenetic environments.

In the Óbarok bauxite, *siderite* was identified both in the muddy matrix (by XRD) and in the fossilized tree-trunk (by optical microscopy), however, its conversion into a haematitic pseudomorph was also observed (see under „Mineralogy" and on Fig 26).

The presence of siderite can be taken as the evidence for the porewater having been of *meteoric* origin at the beginning of the story while hematitization (oxidation) of siderite shows that after siderite formation (in the meteoric phreatic diagenetic environment) conditions must have changed for vadose again to result in oxidation. The so many iron mobilization/precipitation phenomena observed on the meso- and microscale of the Óbarok deposit suggest that the upraisal of the groundwater-table associated with sea-level rise must have oscillated maybe also because of the oscillating fresh-water influx (maybe a result of the strongly seasonal rainfall).

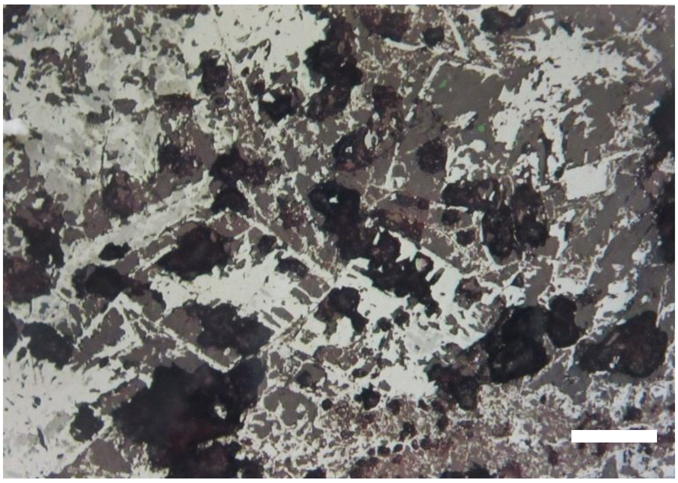


Fig. 26 Haematitic pseudomorphs after siderite in the fossilized Dacrydioxylon. (Óbarok-XI. quarry) Reflected light, scale bar: 125µm (photo by L.Rákosy)

Minor amounts of pyrite, occurring at places in the form of finely dispersed, cubic crystals show that finally, as transgression proceeded, porewaters became gradually more and more saline and thus the destruction of organic matter not yet reacted to form siderite could promote the precipitation of pyrite, too. Telogenetic contact with late, postburial influx of meteoric waters, however, might have resulted in re-oxidation of both sulphur and iron-bearing phases formed during the reducing episodes of diagenesis. That iron -mobilization and reprecipitation induced by redox changes was apparently not restricted to plant-fossils is indicated also by late hematite-fillings ocurring in joints and fissures of the bauxite and frequntly seen in the outcrops.

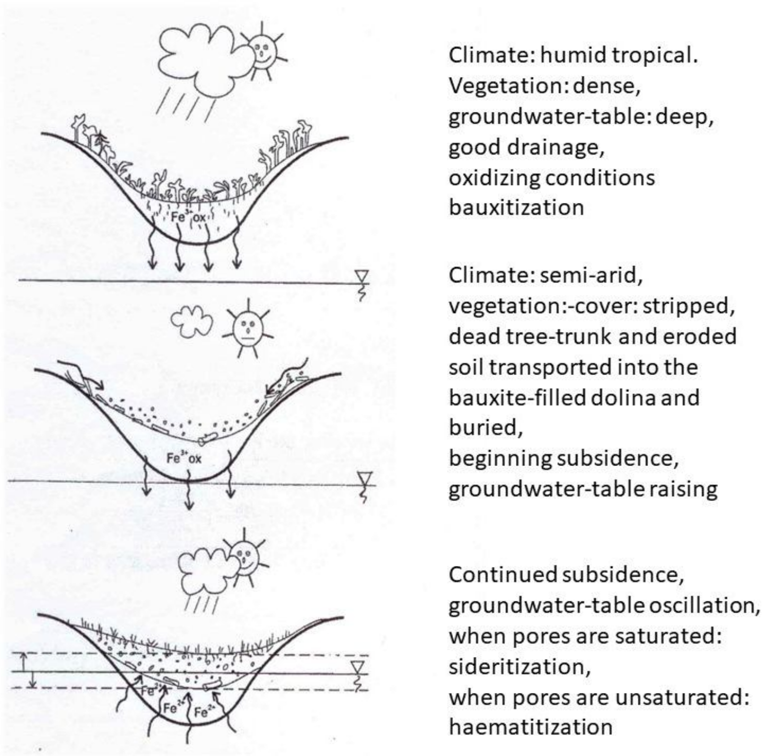


Fig. 27 Cartoon showing the tentative reconstruction of the sequence of events resulting in the early diagenetic mineralization of the Dacrydioxylon remnants found in the Óbarok bauxite (after Mindszenty et al. 2002)

The spectacular paleokarst surface exposed by the Óbarok-XI. bauxite quarry

Under the bauxite the dolomitic bedrock exhibits a crenulated mezo-relief – essentially a fossilized *karrenfeld* – which is exposed by the southern wall of the quarry, where a major fault has cut the deposit into two. When looking at it from close, the angular unconformity between bauxite and its bedrock is obvious. In fact this is a *text-book example* of long-lasting subaerial exposure brought about by tectonically controlled uplift – apparently resulted by eoalpine deformation of the area. The dark contour seen at the boundary between bedrock and bauxite is an iron-rich (haematitic) encrustation underneath of which, for about 10 to 20 centimeters the dolomite is strongly de-dolom itized and impregnated by haematite. Both the crust and the impregnated dolomite are only moderately rich in manganese (MnO: 0,35%) but do not show any particular enrichment in REE's. For a long time the iron-rich crust has been considered as a result of pH-controlled precipitation on contact with the dolomite (=alkaline pH), from meteoric waters percolating through the accumulated bauxite, however the lack of REE-enrichment seems to contradict this idea. Detailed evaluation of data collected in the frames of the REEBAUX project may hopefully shed some light on this issue.

Fig. 28 Karst-relief formed on Triassic dolomite and buried by Oligocene bauxite at Óbarok. It is the result of a tectonically controlled major regional unconformity related to eoalpine deformation of the Transdanubian Range

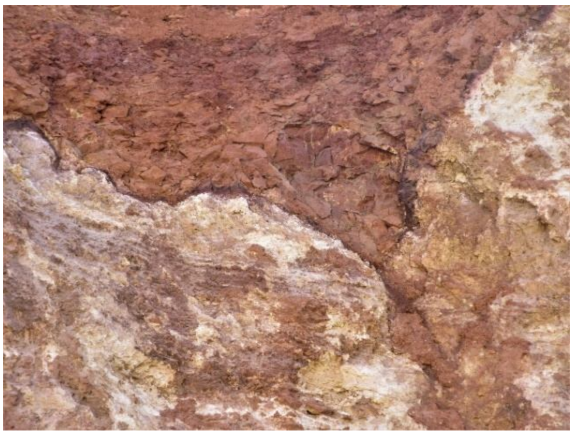


Fig. 29 Detail of the ironoxide-encrusted surface of the karstified bedrock of the bauxite

Closing remarks

The introduction of these two examples of Palaeogene bauxites of Hungary were intended to illustrate the importance of the role of **palaeorelief** and **palaeohydrology** in controlling sedimentological and geochemical processes shaping the lithology and goechemistry of karst bauxites in general andthose exposed at Gánt and Óbarok in particular.

As we have seen: both subaerial relief and hydrology and therefore redox-**conditions** are changing in concert throughout bauxite deposit formation. At the beginning, when relief is high and drainage is perfect, the environment is **oxidizing.** The beginnings of transgression bring about a substantial change in hydrology: the environment becomes „saturated" i.e. **reducing.**

*These general rules should be kept in mind all over the ESEE Region when we are looking for bauxites enriched in Rare Earths, many of which are highly **redox-sensitive** elements*

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