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Bauxites and related paleokarst: Tectonic and climatic event markers at regional unconformities

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Key words: Bauxites, paleokarst, paleoclimate, tectonics, eustasy, anoxia, Cretaceous, Mediterranean

ABSTRACT

This paper is an attempt to show how bauxites and related paleokarst phenomena, occurring at regional unconformities, may contribute to reveal interrelationships between tectonics, eustasy and climate, and at the same time help to understand the anatomy of the unconformities they occur in. Based on the study of examples mainly from the Cretaceous of the Mediterranean, it is suggested that karst bauxites are **regional markers of global events**. Their abundant occurrence in particular intervals in the stratigraphic record indicates the **coincidence** of globally **warm and humid climates** with **tectonically controlled exposure** of extensive (actual or former) carbonate platform areas, and with **peak intensities of explosive volcanism.**

RIASSUNTO

Le bauxiti ed i processi paleocarsici associati, che caratterizzano molte discordanze regionali, consentono di comprendere le relazioni tra tettonica, eustatismo e clima ed allo stesso tempo sono uno strumento analitico per studiare l'anatomia delle discordanze regionali. In base ad esempi tratti dal Cretacico dell'area mediterranea gli autori propongono l'idea che le bauxiti carsiche siano **markers regionali di eventi globali**. La loro frequente presenza in particolari intervalli stratigrafici indica la **coincidenza** di **periodi climatici globalmente caldi ed umidi** con **l'esposizione subaerea controllata dalla tettonica** di estese aree di piattaforma carbonatica (attuali o del passato) in corrispondenza anche con **picchi di intensità del vulcanismo esplosivo.**

1. Introduction

1.1 What are bauxites?

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. There are millions of chemical and mineralogical analyses available from bauxite deposits all around the world. However, most of them were done on bulk samples, irrespective of the lithology of the samples studied.

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MAJOR BAUXITE MINERALS

Alumina minerals	Iron minerals	Ti-mineral	Silicate mineral
Gibbsite γ-$Al(OH)_3$	**Goethite** α-$FeO(OH)$	**Anatase** TiO_2	**Kaolinite** $Al_4(OH)_8(Si_4O_{10})$
Boehmite γ-$AlO(OH)$	**Hematite** Fe_2O_3		
Diaspore α-$AlO(OH)$			

Fig. 1. Major bauxite minerals.

The first isolated attempts to consider bauxites as ordinary sedimentary rocks date back to the 1960's and concern mainly those called "karst bauxites" (D'Argenio 1963, Nicolas 1970; Sinkovec 1970; Valeton 1972; Combes 1972; Bárdossy 1973; Özlü 1978).

1.2 Karst bauxites – the state of the art

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) paleoenvironmental information about those periods which – because of nondeposition or erosion – are not represented by marine sediments (~ unconformity- or disconformity-related "lacunae").

Based on observations in France, Hungary and Greece, Combes (1969), Komlóssy (1970) and Valeton (1972) were the first to come to the conclusion that the mineralogy of karst bauxites faithfully records the redox conditions of the depositional environment, and that 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) (see also 2.2. and Fig. 1, 2).

Nia (1967), Valeton (1976), Combes (1978, 1984), Mindszenty (1983) and D'Argenio et al. (1987) have suggested that the textures/structures of bauxites and the geometry of the karst morphology they fill, may be informative in the context of the paleorelief. They showed that 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 (see also 2.1.).

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

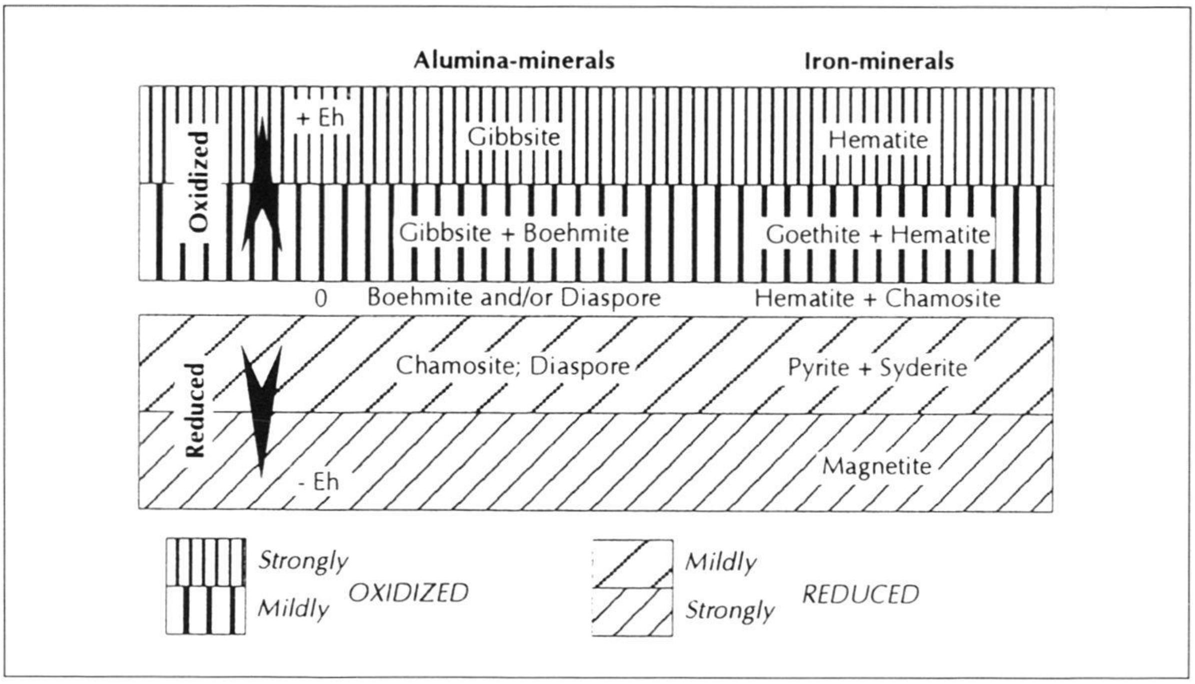


Fig. 2. Characteristic mineral parageneses of bauxites reflecting the redox conditions of the depositional/diagenetic environment.

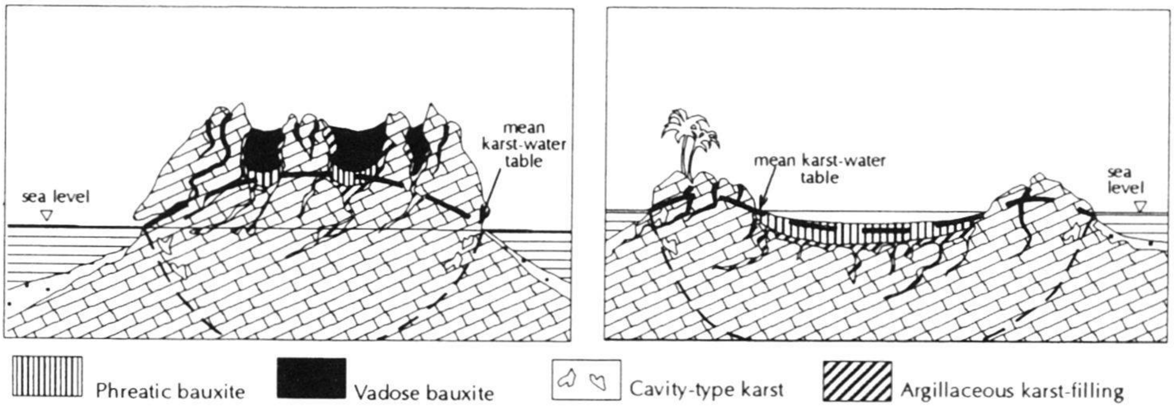


Fig. 3. Schematic models of "vadose" and "phreatic" bauxite formation (from D'Argenio et al. 1987).

reveal information about the relative paleo-altitude of larger crustal segments as well (Combes 1978, 1984, 1990; Komlóssy 1978; Mindszenty 1983, 1984; Valeton 1985; Mindszenty et al. 1986; D'Argenio et al. 1987; Juhász 1988; Juhász & Bárdossy 1989; Fig. 4).

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 tec-

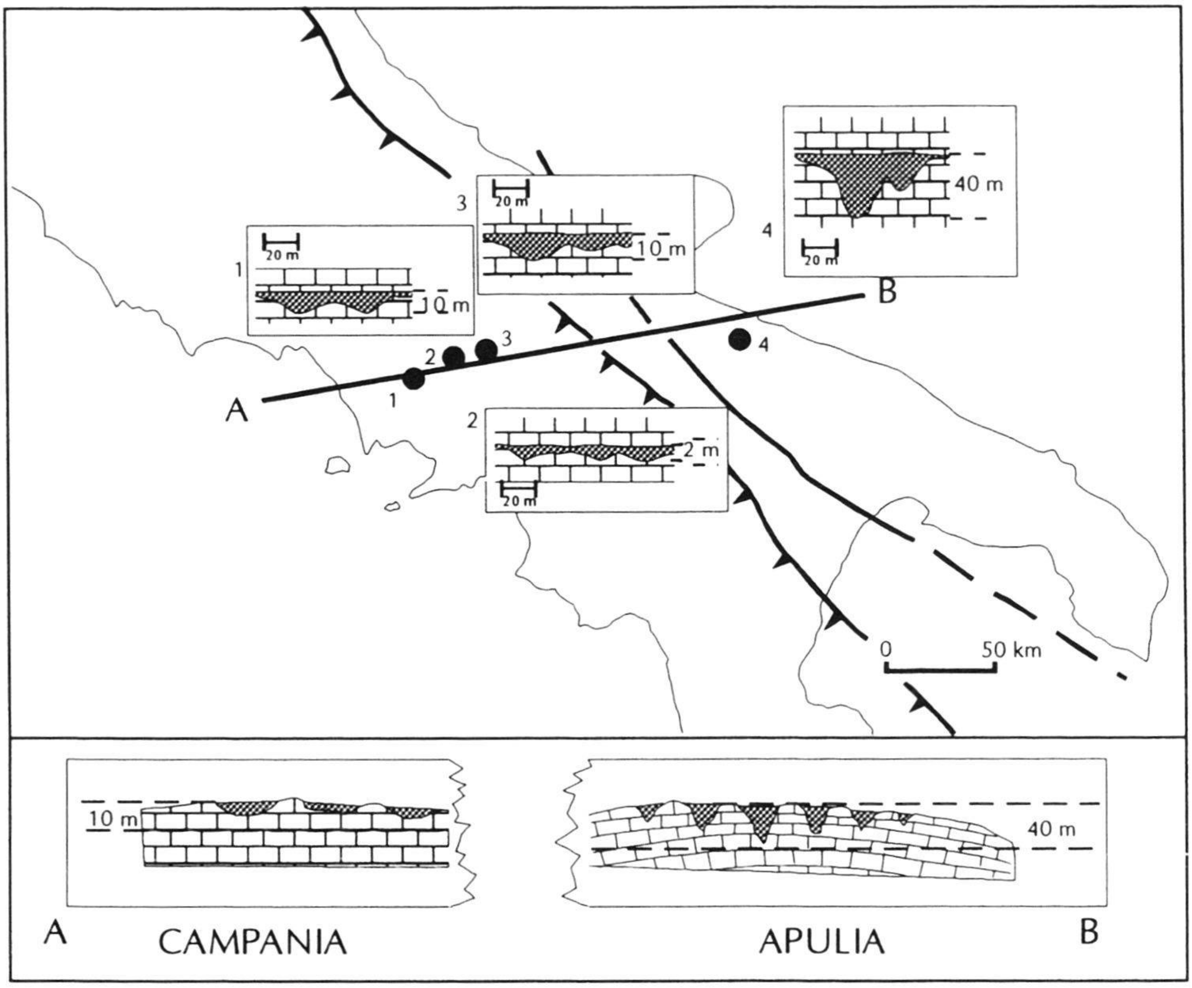


Fig. 4. Lithology and geochemistry of bauxite, as well as morphology and vertical amplitude of the underlying karst relief, reflect the relative paleoaltitude of corresponding crustal segments. The example comes from Southern Italy, where the Matese-M.te Maggiore bauxites (1 to 3, Campania) show shallow karst morphology, whereas Apulia (4) displays a deeply dissected karst relief.

tonic events otherwise not even suspected (Knauer & Gellai 1978; Combes & Peybernes 1987, 1991; Carannante et al. 1987, 1994; Mindszenty et al. 1988; Combes 1990).

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 (Kiss 1955; Vörös 1958, 1969; Antal 1973; Sinkovec 1973; Vörös & Gecse 1976; Susnjara & Scavnicar 1978; Gecse 1980; Mindszenty 1984; Mindszenty & Gál Sólymos 1988; Mindszenty et al. 1991; Dunkl 1992).

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 (Bárdossy 1973, 1979, 1982, 1986; D'Argenio & Mindszenty 1987; Bárdossy & Dercourt 1990; Combes 1990).

The present paper is an attempt to show how bauxites and related paleokarst phenomena occurring at regional unconformities may contribute to reveal interrelationships

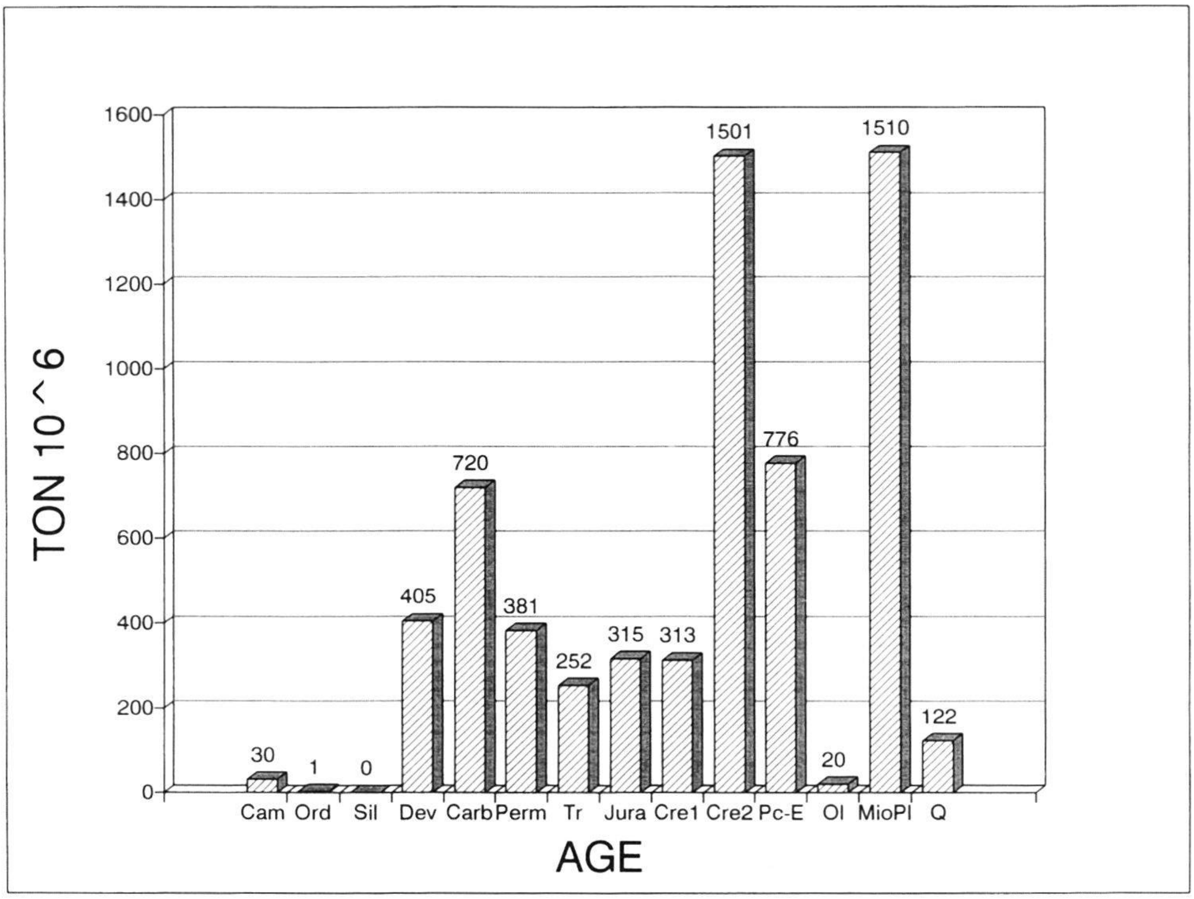
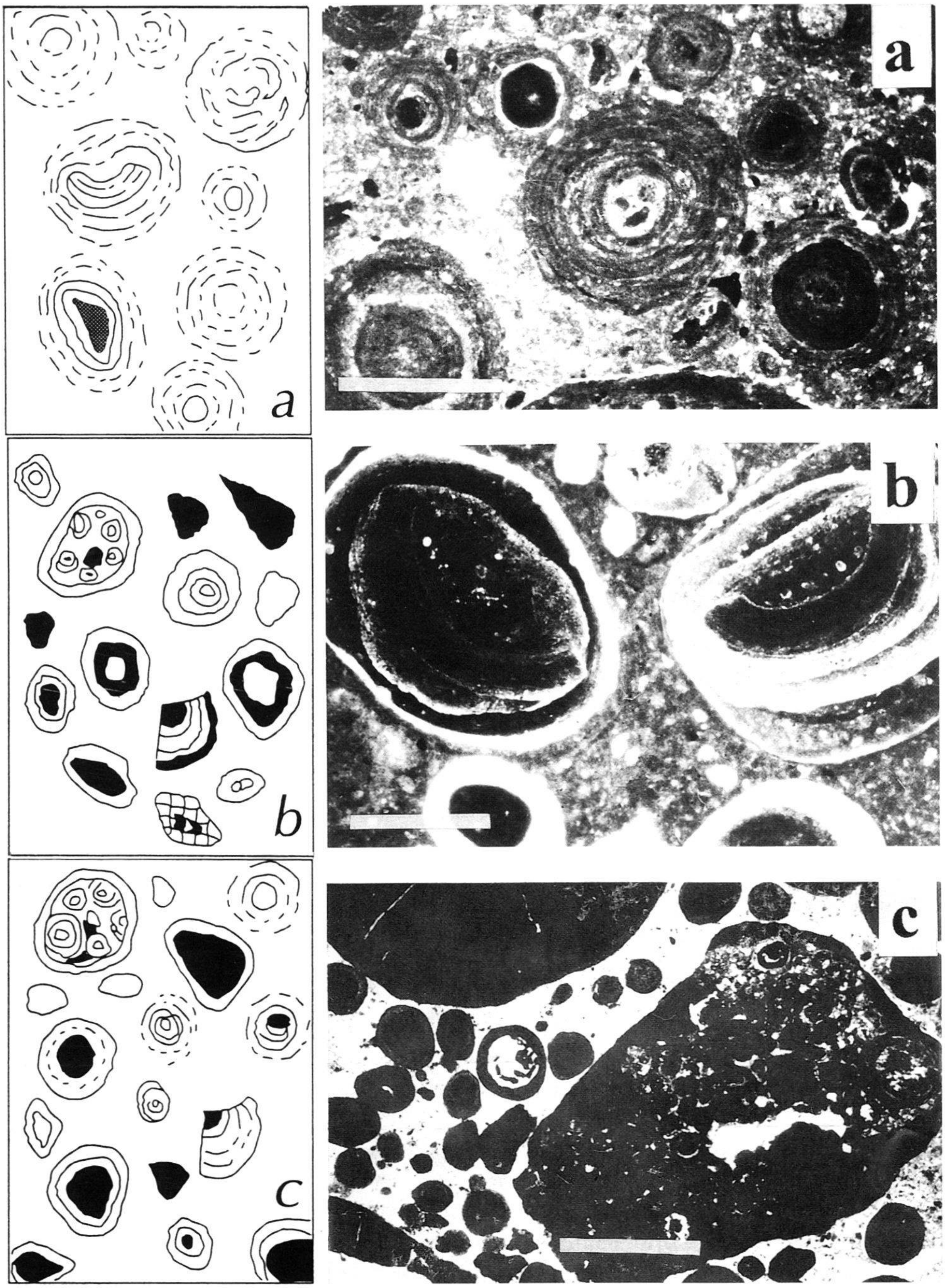


Fig. 5. Estimated reserves of world karst bauxites in 10^6 tons (data from Bárdossy 1982).

between tectonics, eustasy and climate, and at the same time help to understand the anatomy of the unconformities they are associated with.

1.3 Economical vs. Geological interest

Only 11.6% of the bauxite reserves of the world occur in karst related deposits (Fig. 5). However, all the economy-grade deposits of the Mediterranean belong to this group (Bárdossy 1989). Bauxites of the Mediterranean, therefore, readily offer themselves as an example, through the study of which the general understanding of controls on karst bauxite formation may be improved. Main producers of bauxite in this district are Greece, Hungary, Romania, Italy, Turkey, Croatia and Bosnia. Additional smaller-scale occurrences are known from Spain, France, Austria, Slovakia and the ex-Soviet Union. Although the ages of Mediterranean bauxites cover a rather wide time-span (from Triassic to Eocene), most deposits are Cretaceous, implying that this period was particularly favourable for karst bauxite formation. All deposits are associated with local or regional unconformities interrupting shallow-water carbonate sequences, and they are all supposed to have been brought about either by orogenic/epeirogenic movements or by eustatic sea-level changes (Bárdossy 1973; D'Argenio & Mindszenty 1987; Combes &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Peybernes 1989; Combes 1990; Bárdossy & Dercourt 1990). Deposits of greatest economic interest occur always at regional unconformities (e.g., in Hungary or ex-Yugoslavia), whereas deposits related to local unconformities generally are of smaller areal extent and consequently of lesser economic interest (e.g. in Spain or Sicily).

To understand the controlling factors in the emplacement of karst bauxites, it is necessary to review their sedimentology and relationship to bedrock and cover, and then to fit them into a reasonable paleotectonic framework.

2. Karst Bauxites as sedimentary rocks

2.1 *Source, allochthony, autochthony*

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 (Fig. 6). 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 (Bonte 1970; Komlóssy 1970; Combes 1972; Bárdossy 1982; Mindszenty 1989; Valeton 1991; Fig. 7).

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

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Fig. 6. Characteristic karst bauxite textures: (a) autochthonous, (b) parautochthonous and (c) allochthonous textures.

(a) Predominant autochthonous texture with accretional rims formed in situ around "cores". Bar scale: 500 μm

(b) Parautochthonous texture with broken oolite encrusted, broken, and again encrusted. Bar scale: 250 μm

(c) Allochthonous texture with oolitic intraclastic bauxite pebble and iron-rich round-grains/oolites embedded in a deferrified matrix. Bar scale: 250 μm

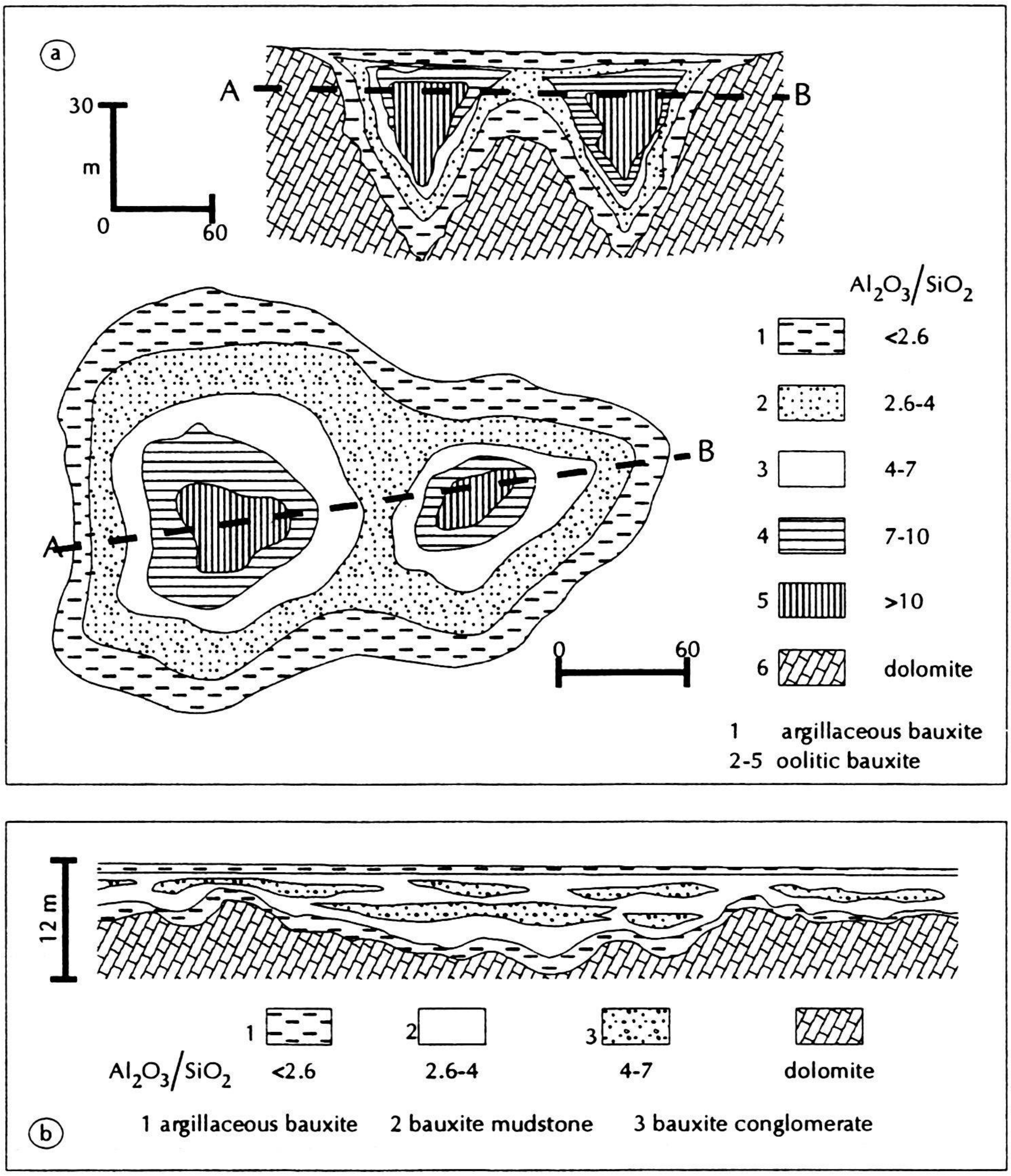
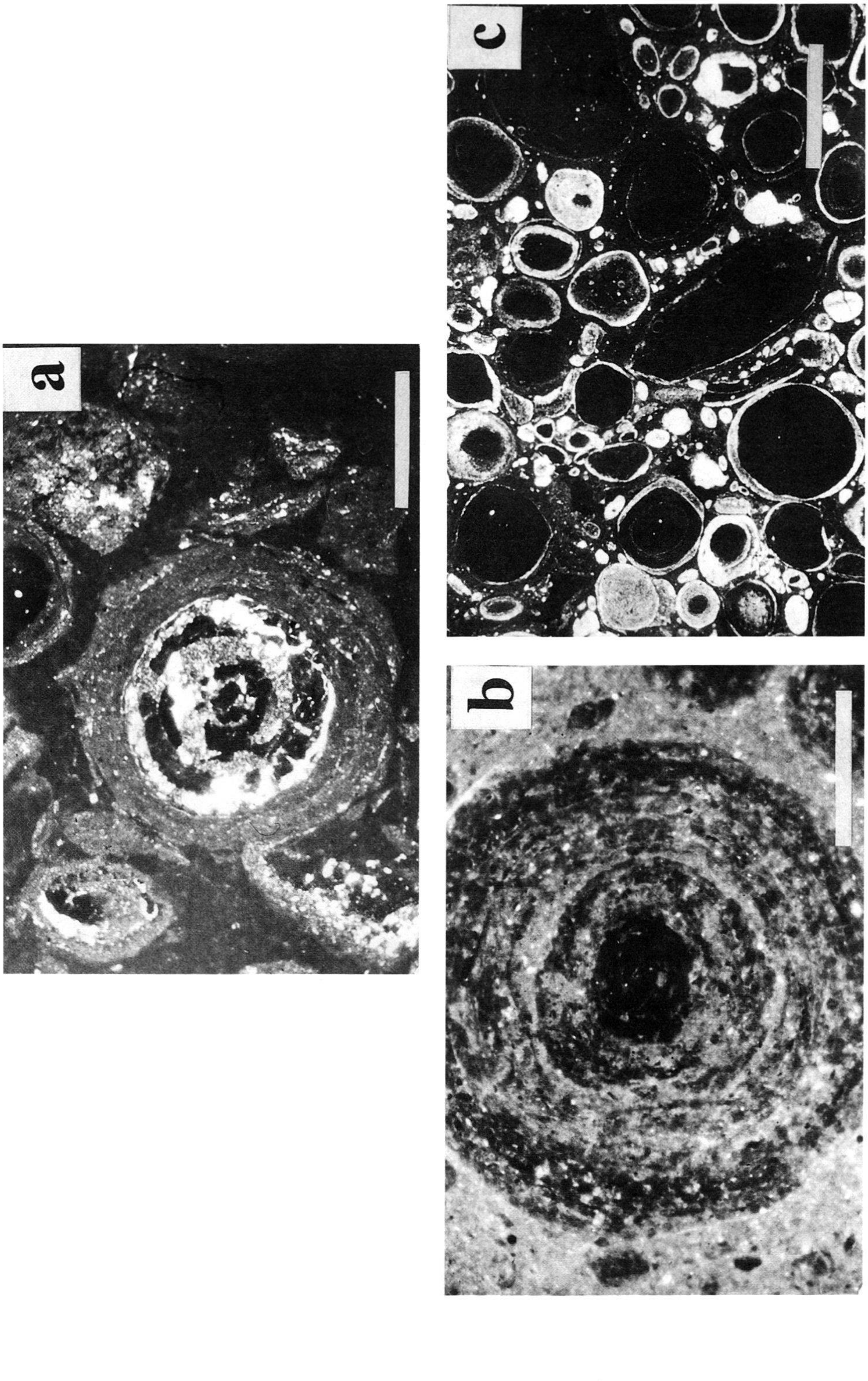


Fig. 7. **(a)** Grade pattern of an autochthonous bauxite deposit (Németbánya, N. Bakony, Hungary; simplified after Südi 1981). **(b)** Grade pattern of an allochthonous deposit (Gánt, Vértes Hills, Hungary; simplified after Mindszenty et al. 1989).

Fig. 8. **(a)** In situ-formed "autochthonous" segregational oolite (bar scale: 250 μm); **(b)** in situ-formed "autochthonous" accretional oolite (bar scale: 250 μm); **(c)** texture suggesting intense, predominantly parautochthonous transport (bar scale: 500 μm).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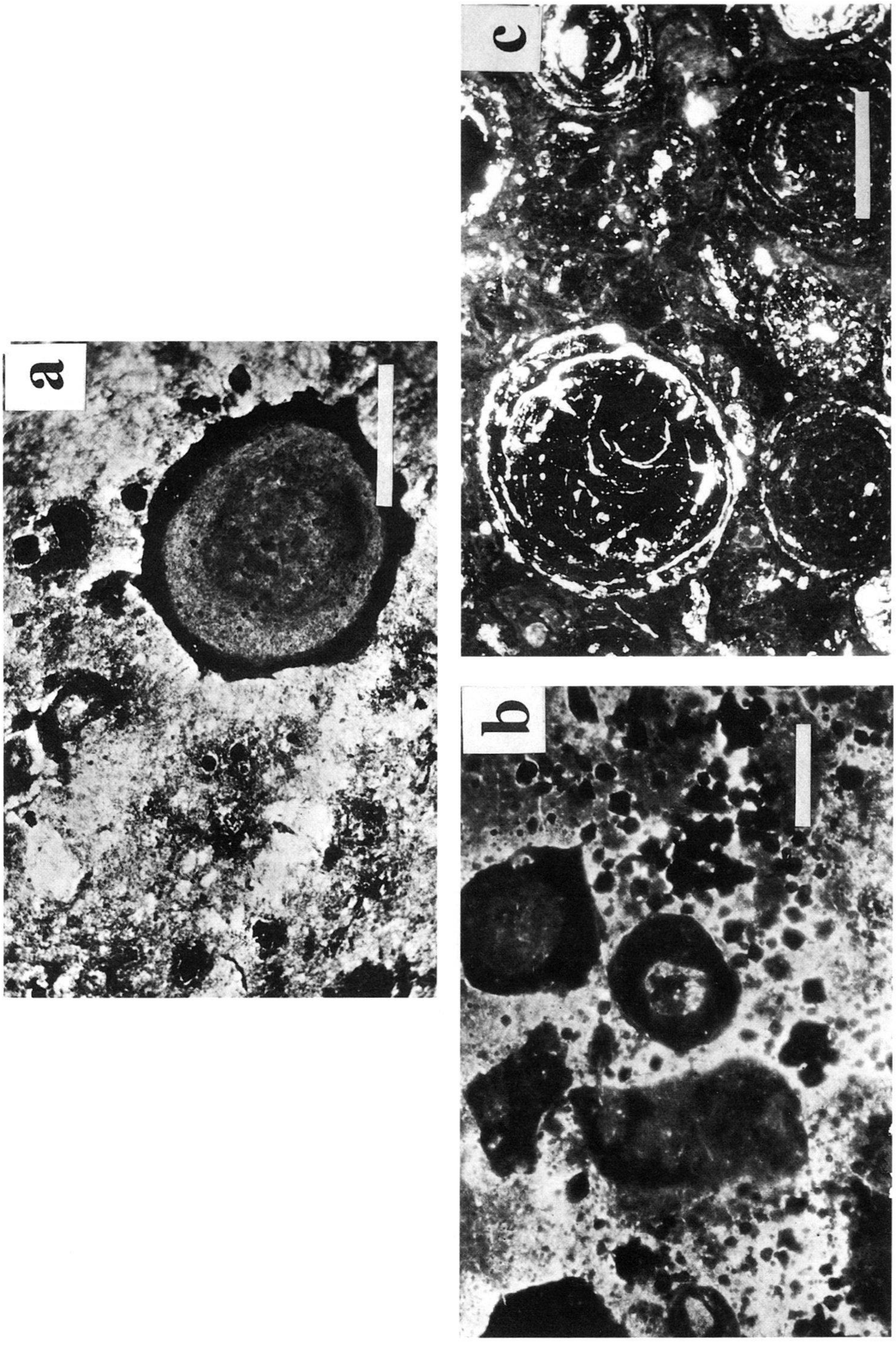
most cases there is ample evidence that the prebauxitic material was brought to the karst terrain by wind or water-induced transportation (Nicolas & Lecolle 1968; Nicolas 1970; Bárdossy et al. 1977; Mindszenty 1983; Mindszenty et al. 1988, 1991).

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 can not 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; Fig. 7, 8).

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 1970; 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., Fig. 8) 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).

Fig. 9. Characteristic textures of "vadose" and "phreatic" bauxites. **(a)** Pyritic, kaolinitic bauxite (phreatic facies; bar scale: 250 μm) **(b)** Pyrite crystals scattered in pale deferrified bauxite matrix (phreatic facies; bar scale: 250 μm), **(c)** Red, oolitic bauxite (vadose lithofacies; bar scale: 500 μm). Note how oolites of different degree of segregation are juxtaposed, suggesting rather intense parautochthonous transport.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2.2 Geochemistry of the depositional/diagenetic environment

The geochemistry of the depositional/diagenetic environment of bauxite formation can be characterized at its extremes as "vadose" and "phreatic" (Lapparent 1935; Valeton 1972; Combes 1969, 1984; Bárdossy 1982; Komlóssy 1970, 1985; Mindszenty 1984; Mindszenty et al. 1986). (The terms "vadose" and "phreatic" are used here in the classical sense, i.e. they refer to the position of the site of accumulation and diagenesis as related to the paleo-groundwater-table which essentially controls the Eh (and pH) of the environment.)

Vadose bauxites (Fig. 9c) ("haut niveau" of Combes) are characterized by the 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 (Schroll & Sauer 1968; Valeton 1972; Maksimovic & De Weisse 1979; Maksimovic 1988; Özlü 1983).

Phreatic bauxites (Fig. 9a, b) ("bas niveau" of Combes) 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 (Maksimovic pers.comm.).

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 (Mindszenty 1989; Mindszenty et al. 1990; Carannante et al. 1994).

Detailed studies of bauxites of the South Bakony (Hungary) and the Southern Apennines (Italy) show that there is a close correlation between the geochemical and lithological facies of bauxites and the karst morphology they are associated with (Fig. 10). 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 (see Fig. 10; cf. with Combes 1984, 1990).

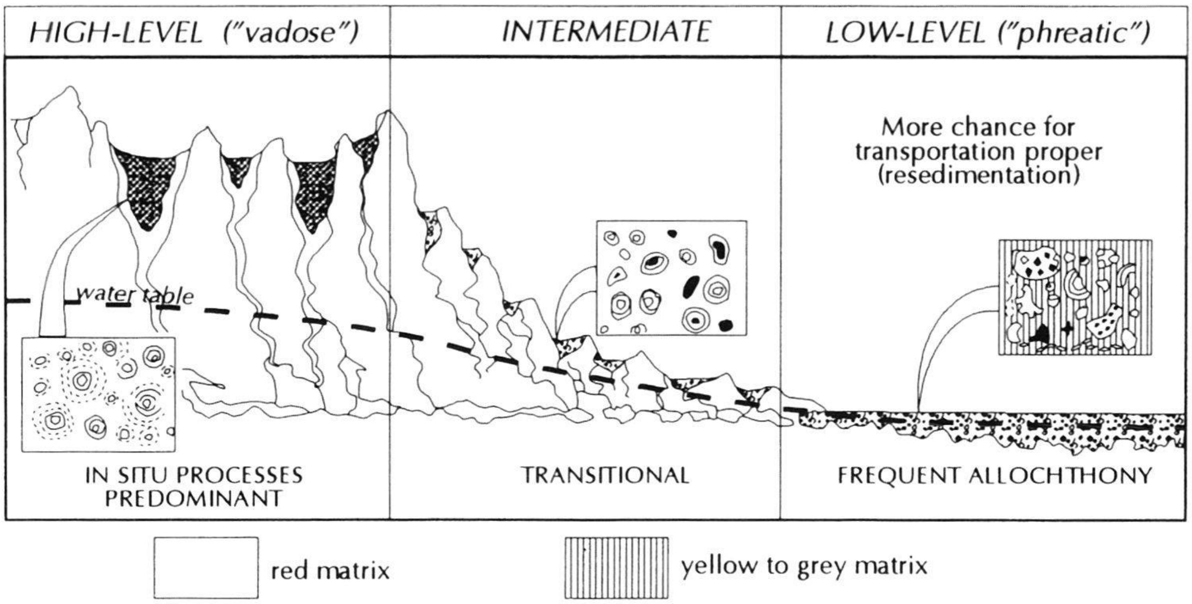


Fig. 10. The catenary relationship of bauxite lithofacies as related to the underlying karst relief (controlled by relative altitude above base level of karst erosion).

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 (Fig. 3, 9, 11).

2.3 Relationship to substrate and cover

2.3.1 Substrate

Any pure carbonate rock may serve as a substrate for karst bauxites. However, in the majority of the cases experience shows, that the substrate is of shallow-water origin. It is their often very high primary porosity which makes shallow water limestones the best candidates to become the host rocks for bauxites, but there are extensive bauxite deposits developed on the surface of more or less restricted, muddy lagoonal facies, too. There may or may not be an angular unconformity between bauxite and its bedrock.

It is generally agreed that the contact between karst bauxites and their substrate is sharp, inasmuch as – unlike laterites – karst bauxites do not develop gradually from their bedrock. However, karstification prior to, during and partly after the deposition of bauxite,

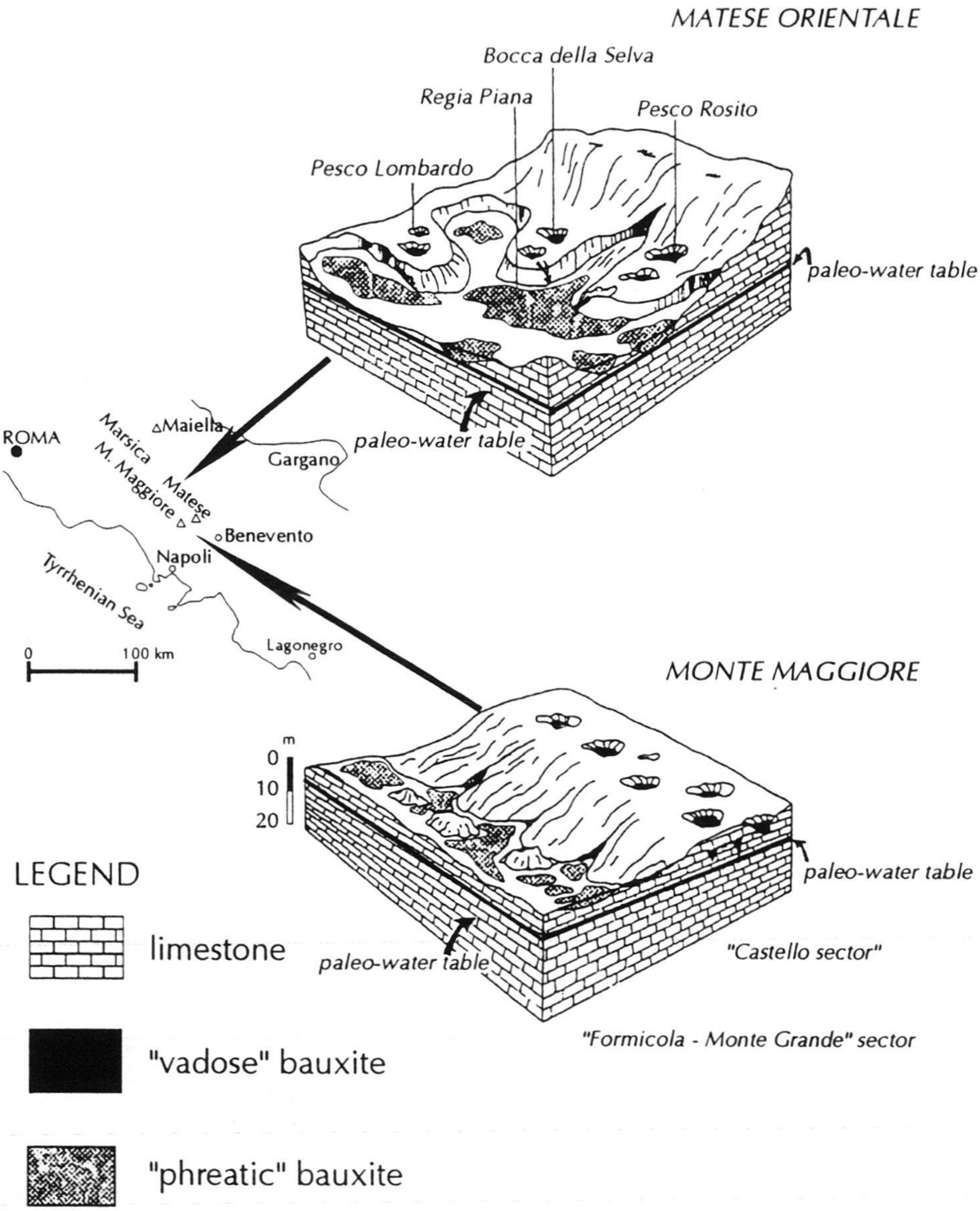


Fig. 11. Lithofacies studies of calcareous bedrock and the overlying bauxite facilitate small-scale paleomorphological restoration of emergent carbonate-platform-interior terrain (Middle Cretaceous of the Campania Apennines) (from Carannante et al. 1994).

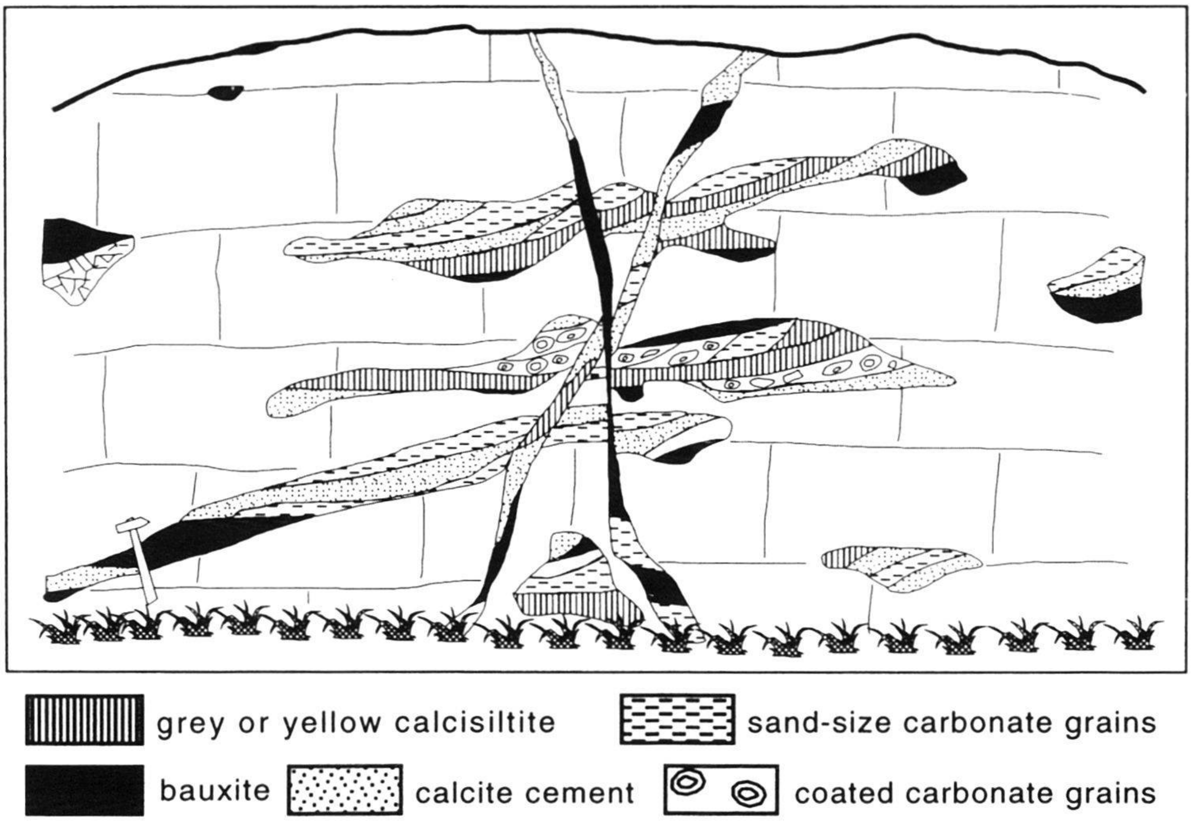


Fig. 12. Meter-scale phreatic-lens related paleokarstic cavities filled by several generations of internal sediment alternating with coarse sparry calcite cement and cut by open fractures (tectonics? compaction?) filled like clastic dykes. Cretaceous of Mte. Camposauro (from D'Argenio 1967).

may alter the bedrock to such an extent that in many cases a transitional altered zone can be recognized between bauxite and the underlying intact carbonate.

2.3.2 Pre- and synbauxitic karst phenomena

Karst phenomena recognized in association with bauxites include surface karst forms (karren, dolinas, sinkholes), vadose or phreatic-lens related underground cavities (random or fissure-controlled), Fe-Mn or Ca-carbonate rich (caliche-like) crusts and impregnations, powdery zones (particularly in dolomites) and dissolution/collapse breccias. The karstic porosity thus created is generally filled by bauxite or bauxitic clay locally intimately intergrown with carbonate (mainly calcite) (Fig. 12).

Systematic studies on bauxite-related karst phenomena are scarce. From the works of Carannante et al. (1974, 1987, 1992, 1994), D'Argenio (1963, 1966a, b), Combes (1978), Boni & D'Argenio (1989), Esteban & Juhász (1990), Juhász & Korpás (1991), Vera et al. (1987) and Molina (1991), it is clear, however, that the twofold division of karst processes and karst terrains (referred to as **mineral-controlled** and **water-controlled** by Lohmann (1988) and as **polymineralic** and **monomineralic** by James & Choquette (1984) respectively) applies very well for the bauxitic karst scenario, too. There are bauxite deposits the karstified substrate of which shows clear signs of **mineral-controlled alteration** of an unconsolidated, **polymineralic sediment**. This kind of alteration is characterized by pervasive microkarst and phreatic cavities of random distribution. The cavities are filled by internal sediment, bauxite fragments and several generations of vadose to phreatic calcite cements. Other bauxite deposits are underlain by bedrock the karstification of which suggests **"water-controlled alteration"** in a **monomineralic system**. Karstic channelways of such systems are tectonically controlled, and are filled predominantly by bauxite, dissolution- and collapse breccia, and with much less cement (mainly vadose speleothems).

Esteban (pers. comm.) suggested to use the name "Caribbean" for polymineralic and "Alpine" for monomineralic karst terrains. We prefer the terms **"early** or **diagenetic"** and **"late** or **epigenetic"** stressing that early karstification overlaps with the diagenesis of the sediment, while late karstification affects an already fully lithified rock.

Since early diagenetic karst processes tend to increase the degree of lithification of the carbonate sediment, early karst phenomena are, after a while, necessarily overprinted by the products of later, epigenetic processes. This means that the degree of preservation of early karst features in initially polymineralic settings, depends on the length of exposure and the intensity of karstification, as discussed by Combes (1978).

2.3.3 Post-bauxitic karst

As recognized by Valeton (1972), Combes (1978), Bárdossy (1982) and D'Argenio et al. (1987) on bauxites of France, Sardina, Southern Italy, Greece and ex-Yugoslavia, karstification of the bedrock may continue even during telogenesis, when bauxites and their bedrocks become subaerially exposed and thus open to the access of meteoric waters again. Superimposed phases of karstification (however, all still qualifying as paleokarst) were described from Cretaceous and Eocene bauxites of Hungary by Mindszenty et al. (1988 and 1991).

2.3.4 Cover

Bauxite deposits may be covered by any kind of continental or marine clastic or carbonate sediments. The overwhelming majority of the economy-grade deposits, however are covered by a transgressive sequence so that marine inundation has preserved them from subsequent erosion. Careful analysis of the cover successions shows that, although there is a wide variety of depositional environments to be recognized above the bauxite, all of them invariably display a more or less continuous transition from fresh water to normal marine conditions (D'Argenio 1963, 1966a; Komlóssy 1970; Mack & Petrascheck 1970; Bignot 1972; Knauer & Gellai 1978; Rákosi & Tóth 1978; Komlóssy & Tóth 1979; Tóth & Knauer-Gellai 1980; Szantner et al. 1986; Carannante et al. 1992).

It was recognized as early as the sixties that lithofacies variations in the immediate cover of a partly bauxite-filled karst terrain reflect the details of the paleorelief (D'Argenio 1963, 1967). In the Parnass-Ghiona area (Greece) Mack & Petrascheck (1970) showed that the lithofacies of the cover above bauxite-filled paleotopographic depressions is different from that above the adjoining barren rock surface. Detailed studies on deposits of the Transdanubian Central Range (Hungary) by Knauer & Gellai (1978), Rákosi & Tóth (1978) and Komlóssy & Tóth (1979) confirmed that these differences are characteristic enough to be used as guidelines in the exploration of bauxites.

2.4 Paleotectonic framework

The relationship between bauxites and tectonism on the small scale has been recognized for a long time. The obvious tectonic control of karstification has been acknowledged and widely used as a guide line for exploration in most classical bauxite countries of the Mediterranean (Dudich & Komlóssy 1969; Károly et al. 1970; Szantner & Szabó 1970; Szantner et al. 1986; Blaskovic et al. 1989). The first attempts to correlate bauxites with large-scale regional tectonics, however, had to wait the advent of plate-tectonics in the seventies.

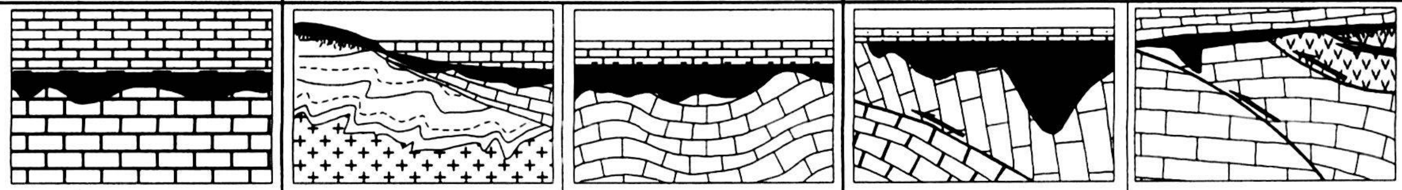
Bárdossy (1973) was the first to try to explain the distribution of karst bauxites in terms of their geotectonic position. He recognized that 85.6% of all karst bauxite deposits of the world occurred in orogenic belts and only 14.4% of them on continental plates. He also pointed out that there was a *"close relationship between the tectonic position of karstic bauxites on the one hand and their type of deposit, petrographic and mineralogic composition and genesis on the other"*. He tried to compare the tonnage of bauxites found in various subenvironments of the orogenic belts and found that 70.4% of them occurred in "geosynclinal belts", 7.9% in "median masses" and 7.3% in "intracontinental orogenic belts", and concluded that *"bauxite deposits could form mainly in areas where continental plates had collided with intervention of microcontinental plates or oceanic microplates"*. However "avant-garde" his views were at that time, he was mislead in his calculations, because instead of using time-slices (not yet available in those times) he took the composite geotectonic map of Aubouin & Durand-Delga (1971) to serve as a basis for qualifying the geotectonic position of bauxites. Thus, for instance, Cretaceous bauxites of Southern Italy formed in a passive carbonate platform environment were qualified as belonging to the "Southern geosynclinal zone". Although his grouping undoubtedly gave an account of the present geotectonic position of the studied bauxite deposits, it failed to give an insight into the true paleotectonic affiliation of the bauxitiferous areas.

The other attempt to fit bauxites into a global tectonic framework worth mentioning was that of Nicolas & Bildgen (1979) who tried to explain the distribution of all karst and laterite related bauxites of the world and paid special attention not only to "continental drift", but also to the shifting of the equatorial belt with time, to the changing intensity of orogeny and orogeny-related volcanism, and to long-range climatic changes. In conclusion they suggested that the global distribution of bauxites may serve as another excellent *"support to the mobilist theories"*.

In the eighties, when plate tectonics already became generally accepted and used as a tool to understand the evolution of smaller regions as well, the relationship between bauxites and tectonics regained interest. Mindszenty et al. (1984) and D'Argenio & Mindszenty (1987a, b), in their comparative estimate on Cretaceous bauxites of Austria and Hungary, suggested that similarities and differences between the bauxitiferous successions of the two areas recorded similarities and differences between the tectonic evolution of the studied bauxitiferous terrains.

According to their observations the angular unconformity between bauxite and bedrock was distinct in both areas suggesting that subaerial exposure was brought about in both cases by intense tectonic deformation. The different timing of the exposure, however, would clearly show that deformation in the two areas was not synchronous. Despite the apparent diachronism of uplift, the mineralogy and geochemistry of bauxites, and also the geometry of the deposits proved to be strikingly similar, reflecting that climatic and geomorphological con-

KARST BAUXITES OF THE MEDITERRANEAN

PALEOGEODYNAMIC POSITION	PLATE INTERIOR of the Adria plate	PLATE MARGIN: EUROPEAN "FORELAND"		PLATE MARGIN: NAPPE PILES PROXIMAL TO THE COLLISIONAL BELT	
SCHEMATIC GEOLOGIC SETTING					
TYPE DISTRICTS	SOUTHERN ITALY EXTERNAL DINARIDS	PROVENCE PYRENEES	SARDINIA PYRENEES	NORTH. CALCAREOUS ALPS TRANSDANUBIAN CENTRAL RANGE	INTERNAL ZONES OF DINARIDS-HELLENIDS
ORIGINAL GEOTECTONIC LOCATION	ISOLATED CARBONATE PLATFORMS	ATTACHED (EPICONTINENTAL) CARBONATE PLATFORMS OF NON-DEFORMED (OR MODERATELY DEFORMED) FORELAND, INCLUDING TRANSCURRENT CONTINENTAL MARGINS		CARBONATIC NAPPES of COLLISIONAL BELTS: WITHOUT MAJOR OPHIOLITES	CARBONATIC NAPPES of COLLISIONAL BELTS: WITH MAJOR OPHIOLITES
APPARENT STRATIGRAPHIC GAP	SMALL 1 to 3 My	SMALL to MEDIUM 1 to 10 My		MEDIUM to LARGE >10 My	
ANGULAR UNCONFORMITY	SMALL to NIL	MODERATE to NIL		VARIABLE (MAY BE GREAT)	SMALL to MODERATE
SUPPOSED SOURCE MATERIAL	WINDBLOWN DUST, PYROCLASTICS, CARBONATE RESIDUE	SURFACE TRANS-PORTED WEATHERING PRODUCTS +WINDBLOWN DUST +?PYROCLASTICS	DISSOLUTION RESIDUE +WINDBLOWN DUST +PYROCLASTICS	SURFACE TRANSPORTED WEATHERING PRODUCTS (ALSO OF OPHIOLITES) +WINDBLOWN DUST +?PYROLCASTICS +CARBONATE RESIDUE (TRACE ELEMENTS: Ni, Cr!)	
UNDERLYING KARST RELIEF	SHALLOW to MODERATE 1-10 m	SHALLOW to MODERATE 1-50 m		VARIABLE up to 100 m	VARIABLE up to 50 m
PHREATIC-LENS RELATED DISSOLUTION FEATURES	VERY ABUNDANT	ABUNDANT to MODERATE		SCARCE	
CHANGES OF CARBONATE FACIES ACROSS THE UNCONFORMITY	ESSENTIALLY UNCHANGED	MINOR to MAJOR CHANGE		SUBSTANTIAL CHANGES	VARIABLE

ditions of bauxite formation were similar in both areas. Opposite to this, the story reflected by the lithofacies of the coverbeds points to increasingly different evolution of the two areas in postbauxitic times: coverbeds are predominantly terrestrial and shallow marine in Hungary while quickly changing to deep-marine in Austria, suggesting that subsidence following subaerial exposure was markedly different in the two areas.

A systematic review of bauxites of the Southern Apennines revealed that they probably reflect orogeny-related deformation of the distant, relatively tranquil carbonate-platform environment (D'Argenio et al. 1987; Carannante et al. 1992). Valeton (1987) recognized the role of orogeny-related tectonism in the deposition of Jurassic and Cretaceous bauxites of Greece. Combes & Peybernes (1989) and Combes (1990) argued for a combined eustatic and tectonic control in the case of the bauxite deposits of Languedoc, Provence and Sardinia and emphasized the importance of wrench-faulting. Bárdossy & Dercourt (1990), in their concise review on Tethyan bauxites in which they displayed the paleotectonic position of bauxites on the well-known set of paleogeographic maps of Dercourt et al. (1985), came to the conclusion that *"almost all bauxites were formed on low coastal plains"*. They also emphasized the role of tectonism particulary that of wrench faulting, saying that *"major deposits occur near wrench faults and were formed while the faults were active"*. However, they admit that smaller scale deposits may have formed as a result of any kind of tectonism as well. D'Argenio & Mindszenty (1991), in their paper on Cretaceous bauxites in the tectonic framework of the Mediterranean, tried to reconstruct the paleotectonic position of bauxites of Spain, France, Slovakia, Romania, Austria, Hungary, Italy, former Yugoslavia and Greece by plotting them on the paleogeographic base maps of Ziegler (1988). They recognized that deposits formed on the European "foreland" are markedly different from those formed over "isolated carbonate platforms" of the Adria plate and those occurring on top of nappe piles "proximal" to the margins of the very same plate (Fig. 13). They also argued for the predominance of tectonic control over eustasy, even in the case of the "isolated carbonate platform" settings. In conclusion, they proposed that bauxites could be used as "markers" when trying to correlate the tectonic evolution of orogenically influenced "proximal" and more quiet "distal" areas.

3. Bauxites and related paleokarst. An updated framework

3.1 Bauxites

Trying to improve our model referred to above (D'Argenio & Mindszenty 1991), and incorporating into it some of the elements of the other models previously cited, we propose the following, geotectonically based division of karst bauxites:

(i) Plate-margin (or "proximal") bauxites

(ii) Plate-interior (or "distal") bauxites

Fig. 13. Karst Bauxites of the Meditterranean (simplified after D'Argenio & Mindszenty 1991).

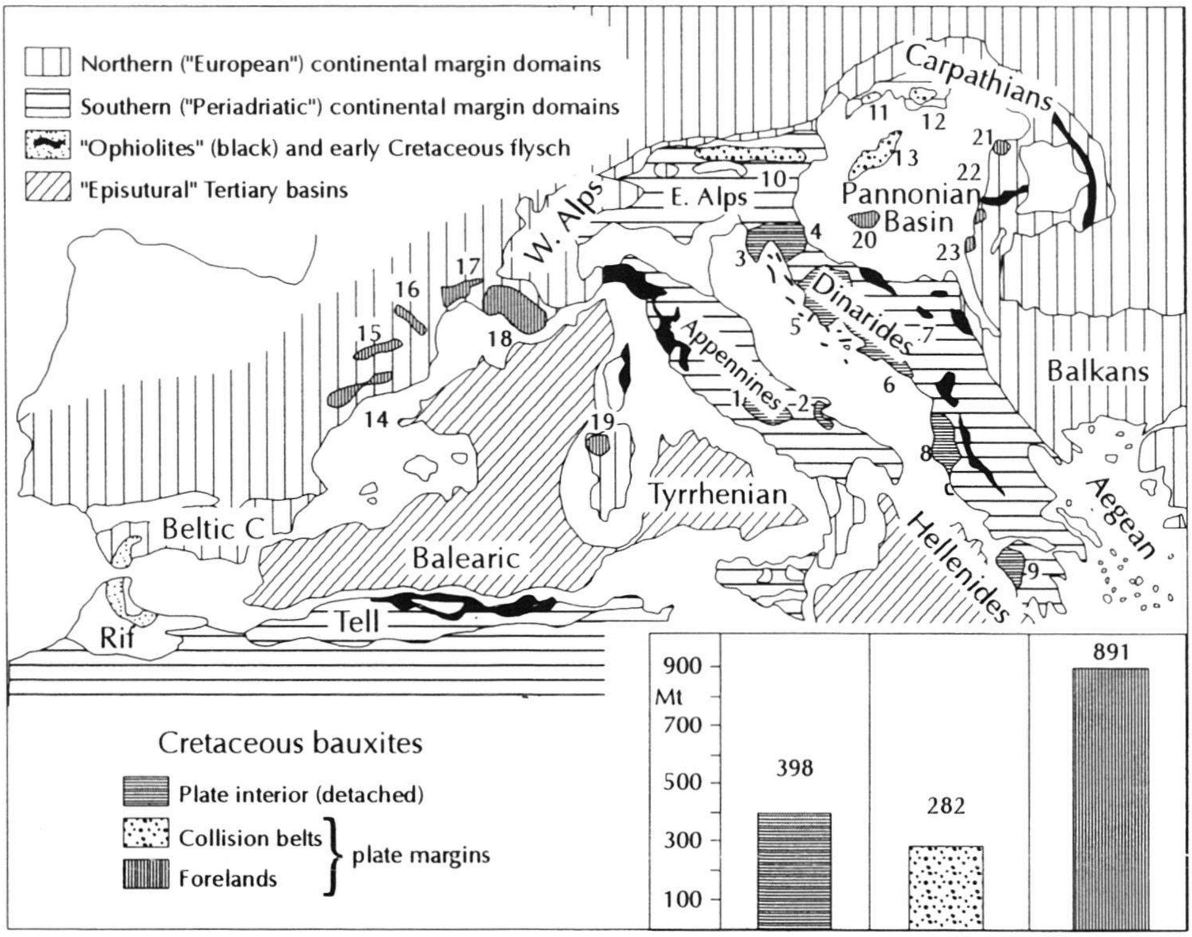


Fig. 14. Cretaceous bauxites of the northern and southern continental margins of the oceanic Tethys. Map from Laubscher & Bernoulli (1977) modified; location of main bauxitiferous areas and respective tonnages from Bárdossy (1982), distinction of principal types based on location of karst bauxites at the time of their formation modified from D'Argenio & Mindszenty (1987). Bauxite districts indicated: 1: Central & Southern Apennines; 2: Apulia; 3: Istria; 4: Slovenia; 5–7: Dinarids; 8: Albanids; 9: Hellenids; 10: Eastern Alps; 11–12: Western Carpathians; 13: Transdanubian Central Range; 14: Catalonia; 15–16: Pyrénées; 17–18: Languedoc-Provence; 19: Sardinia; 20: Villány; 21: Rahov; 22: Bihor; 23: South Transylvania.
As to the volume of karst bauxites: note that the smaller tonnage of collision-belt karst bauxites may be the result of greater amounts of uplift and the associated early erosion. Plate interior bauxites, even though obviously having received lesser amounts of source material (mainly by air, because they were isolated from overland transport of non-carbonate materials), have better chances for preservation, due to rapid fossilization by marine sediments (and therefore less early erosion). The optimum combination of large volumes of source material and lesser vulnerability by early erosion is realized in foreland settings.

This system was worked out for Cretaceous occurrences of the Mediterranean but we suggest it may apply to any other regions and stratigraphic horizons as well (e.g. the Permo-Mesozoic of the Elborz Mts. and Central Iran, the Cretaceous of the Zagros Mts (Sharifi Noorian et al., 1991), the Neogene to Recent of the Caribbean (D'Argenio 1966c) or present-day Papua-New Guinea (Bally, pers. comm.).

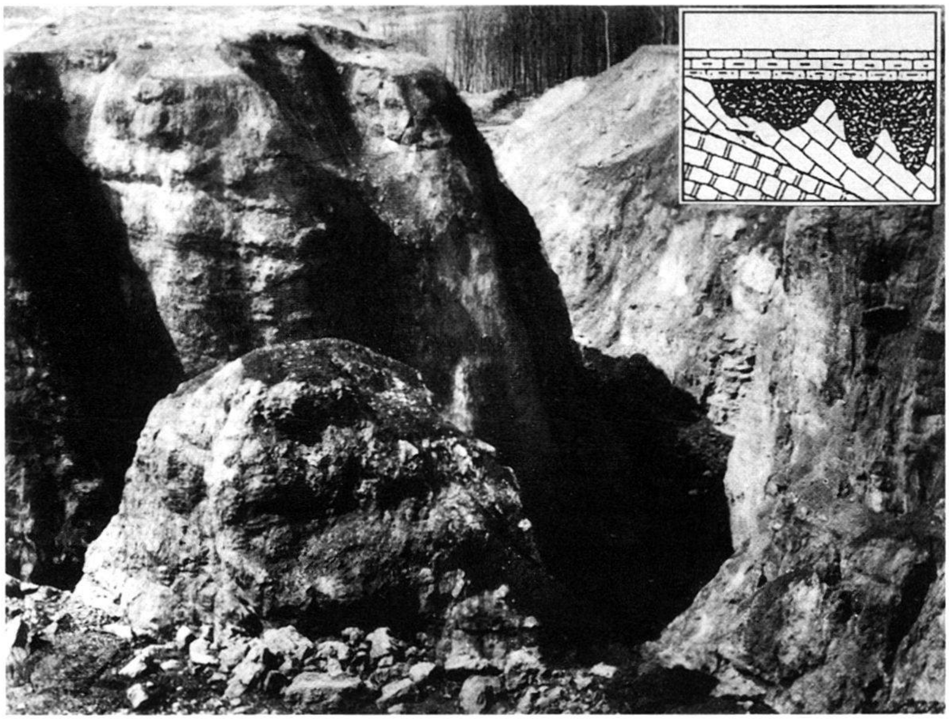


Fig. 15. Orogeny-controlled bauxite, filling deep sinkholes at Németbánya (North Bakony, Hungary). For scale see trees at the upper centre of photo.

(i) Plate-margin bauxites

(i1) On the overriding plate

(Type occurrences: Northern Calcareous Alps (Austria), Transdanubian Central Range (Hungary), Vlasenica and Grebnik (former Yugoslavia), Euboea (Greece), Pogradec (Albania) (Fig. 14)).

In a plate-margin setting on the overriding plate, stacking of nappes and the presence of an orogenic wedge underneath result in large-scale isostatic uplift and, consequently, in intense erosion, related to the high relief (Fig. 15).

In those sectors of the exposed shallow-water carbonates which, due to topographic factors, are sufficiently isolated from coarse clastic influx, fine-grained products of chemical weathering may accumulate and be converted to bauxites. In such settings the source material of bauxites may be any kind of continental-crust or volcanic material and/or the weathering product of obducted ophiolites. This has been shown by numerous micromineralogical and geochemical studies published mainly in Hungary, Austria and Yugoslavia (Kiss 1955; Vörös 1958, 1969; Sinkovec 1970; Dudich 1972; Maksimovic et al. 1983; Caillere et al. 1976; Susnjara & Scavnicar 1978; Gecse 1980; Mindszenty & Gál-Sólymos 1988; Mindszenty et al. 1991). Micro-extraclasts of various composition that indicate the lithology of the denuded non-carbonate rock-suites are frequently recovered from the micromineralogical residue of bauxites occurring in plate-margin settings.

Since subaerial exposure is brought about here by orogeny-controlled tectonism, bauxites overlay the carbonate substrate with an angular unconformity. Also, because of the high tectonically controlled relief, erosional removal of the exposed rocks may be substantial. Bauxites occurring in such deeply eroded terrains are therefore commonly associated with large stratigraphic gaps (10 to over 100 My) the greater part of which is erosive and only a minor part is due to non-deposition. In the plate-margin setting, ophiolite-related bauxites are the only ones associated with smaller stratigraphic gaps (5 to 12 My). They reflect the rather particular depositional environment in the vicinity of ophiolites overthrust/obducted along low-angle faults, onto flat-lying shallow-water carbonates.

The lithofacies of the cover of bauxites formed in the plate-margin setting (particularly on the overriding plate) is always substantially different from the lithofacies of the underlying substrate (e.g., bauxites of Hungary and Austria are underlain by "pure" platform carbonates), whereas in their cover we frequently find clastic sediments rich in continental-crust-derived material provided by erosion of adjoining orogenically uplifted non-carbonate terrains (Ruttner & Woletz 1957; Ruttner 1970; Szantner et al. 1986).

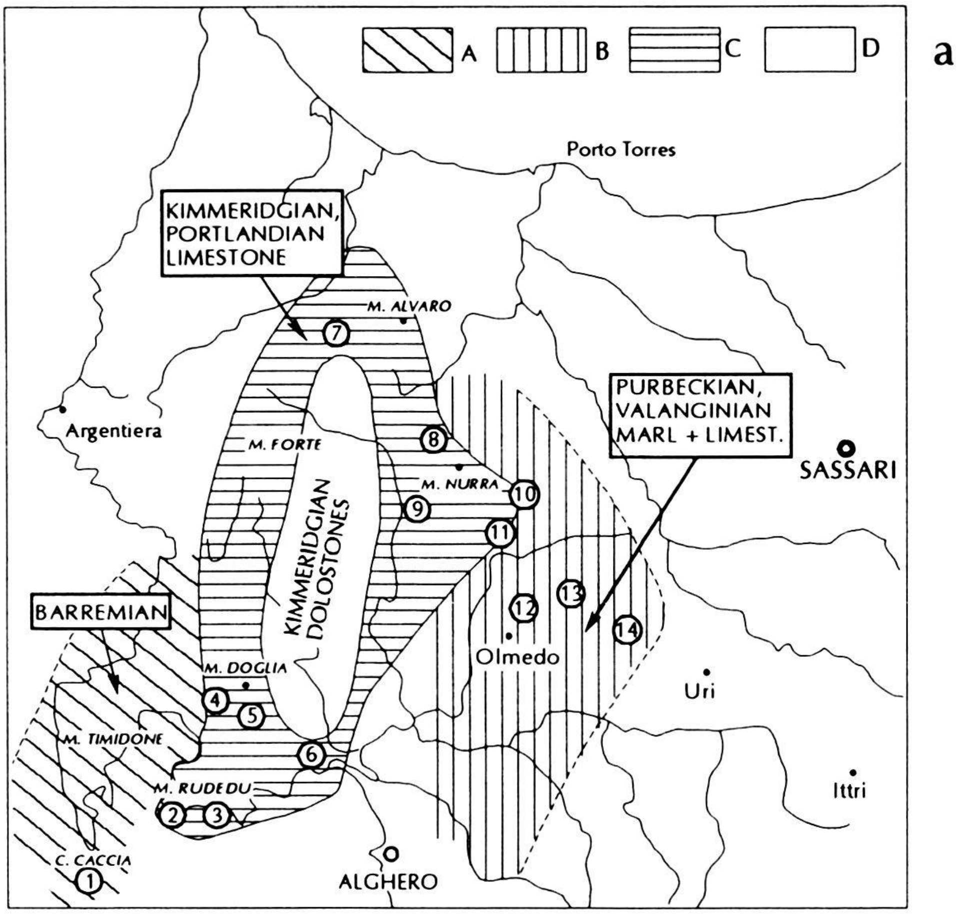
(i2) On the underthrusting plate and along transform margins

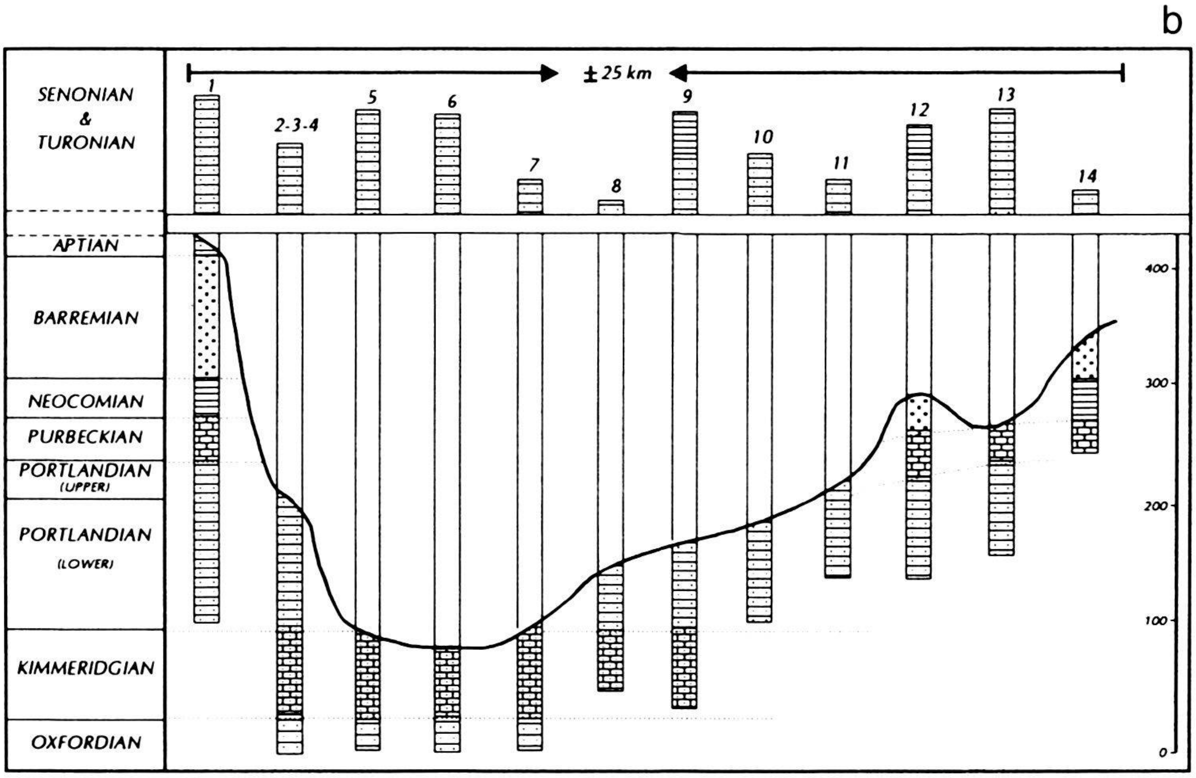
(Type occurrences: Languedoc, Provence, Sardinia, Pyrenees)

On the underthrusting plate geomorphology is controlled by downforcing of the foreland by the tectonic load of the advancing nappes, as a result of which arching-related uplift may take place at the inflexion zone, as suggested by Quinlan & Beaumont (1984), Desrochers & James (1988) and Bosellini (1989) (Fig. 17). Another process leading to uplift may be wrenching, as suggested by Combes (1990) and Bárdossy & Dercourt (1990).

Carbonate platforms attached to the craton, when exposed as a result of any of the above mentioned mechanisms, may be recipients of the weathering products washed down from the adjoining elevated areas by surface waterflows (sheet-wash and eventual temporary watercourses), as shown by Nicolas et al. (1976). Bauxites formed by prolonged weathering of this material in the karstic environment overlie their substrate with variegated but generally gentle angular unconformity (see Combes & Peybernes 1987; Combes 1990). The duration of the stratigraphic gap they occur in varies from short to medium (ca. 8 to 40 My). In fact, large areas of the foreland being situated close to sea level (*"low coastal plains"* of Bárdossy & Dercourt 1990) may be exposed as a result of a complex interplay of tectonics and eustasy, thus producing bauxites occurring in small stratigraphic gaps and intercalated – sometimes repeatedly – within essentially conformable carbonate successions: e.g., the bauxites of Ariège/France as described by Combes & Peybernes (1987) and Combes (1990).

Fig. 16. **a** – Mid-Cretaceous erosional relief in NW Sardinia **(A)** Minimum of erosion (less than 100 m): Turonian Rudistid limestones are underlain by folded Barremian limestones. No bauxites. **(B)** Over 100 m of erosion: the youngest formations below the unconformity are Valanginian limestones. Here the most significant bauxite deposits occur. **(C)** Over 200 m of erosion. Turonian limestones are underlain by Portlandian limestones. Occasional bauxite deposits. **(D)** Over 300 m of erosion: Kimmeridgian dolostones crop out in a narrow belt as the oldest formations below the gap. No bauxites. Numbers in circles refer to the stratigraphic columns below (from Boni & D'Argenio 1989).
b – Mid-Cretaceous emergence in Sardinia. For the exact location of the stratigraphic columns in NW Sardinia/Nurra see Pecorini 1956.


A
B
C
D
a
Porto Torres
KIMMERIDGIAN, PORTLANDIAN LIMESTONE
M. ALVARO
PURBECKIAN, VALANGINIAN MARL + LIMEST.
Argentiera
M. FORTE
SASSARI
M. NURRA
KIMMERIDGIAN DOLOSTONES
BARREMIAN
Olmedo
M. DOGLIA
Uri
M. TIMIDONE
M. RUDEDU
Ittri
C. CACCIA
ALGHERO


b
SENONIAN & TURONIAN
APTIAN
BARREMIAN
NEOCOMIAN
PURBECKIAN
PORTLANDIAN (UPPER)
PORTLANDIAN (LOWER)
KIMMERIDGIAN
OXFORDIAN
± 25 km
1
2-3-4
5
6
7
8
9
10
11
12
13
14
400
300
200
100
0

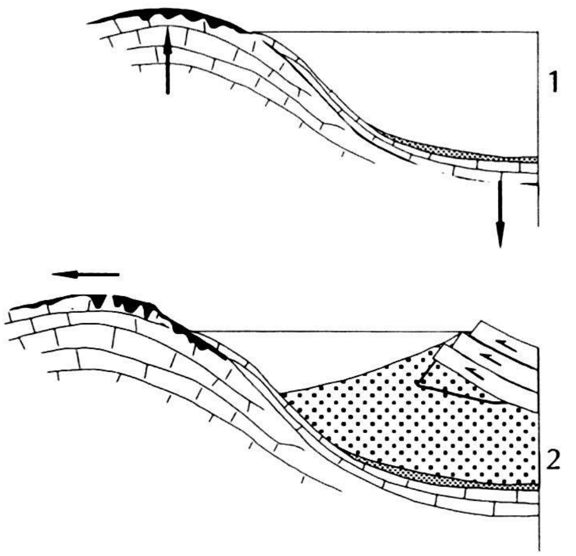


Fig. 17. Possible mechanism of tectonic uplift and karstification of a carbonate platform riding on the underthrusting plate margin – (modified after Quinlan & Beaumont's foreland-deformation model as quoted by Descrochers & James 1988).

(ii) Plate-interior bauxites

(Type occurrences: Southern Apennines, External Dinarids-Hellenids)

It is generally agreed that the internal parts of large lithospheric plates, far from any kind of previous orogenic deformation, are quiet, and that – under suitable climatic/oceanographic conditions – they are characterized by a dynamic equilibrium of continuous, thermally controlled subsidence and carbonate platform growth (e.g., the southern Tethyan margins in Cretaceous times).

The response of such carbonate platforms to relative sea-level falls, or to gentle intraplate-stress induced arching is the subaerial exposure of vast areas of very low relief which, by their potential for karstification, may serve as optimum sites for the accumulation and bauxitization of any kind of wind-blown dust deposited on their surface: e.g. bauxites of Southern Italy as described by Bárdossy et al. (1977), D'Argenio et al. (1987) or those of the External Dinarids mentioned by Sakac & Sinkovec (1991).

As a result, bauxites occurring in plate-interior settings are generally poor in noncarbonate extraclasts; they overlie their substrate with no or only minor angular unconformities (Fig. 18), and the apparent stratigraphic gap they occur in is generally small (1 to 5, at most 10 My). The lithofacies of their cover is always nearly identical to that of their substrate: after a thin (dm to m scale) transitional layer (generally rich in freshwater algae, etc.) platform-type carbonate sedimentation recovers again and continues upwards without any major facies change.

3.2 Paleokarst

Karst features are formed on interaction with meteoric waters of subaerially exposed carbonate sediments and rocks. Inasmuch as karst hydrology is essentially a function of subaerial relief and of its geomorphic history, karst phenomena, observed in association with bauxites, should give us another insight into the details of that relief. Furthermore, since

Fig. 18. Bauxite in intraplate position, conformably intercalated in shallow water carbonates of the Southern Apennines.

the role of tectonics is an important control in the evolution of karst landforms, the study of relief may furnish us with structural geological information, too.

When making an inventory of bauxite-related paleokarst features in each group of the above proposed geotectonic scheme it turns out that the relative abundance of **early** (Caribbean) and **late** (Alpine) karst features follows a logical pattern corresponding to the geotectonic division of bauxites.

Predominant paleokarst features associated with bauxites occurring in **plate-margin settings** (on the *"overriding plate"* with high tectonic relief) are of the **late, epigenetic-type,** with a deep-reaching vadose zone and well-developed extant karst-forms (sink-holes, dolinas, and often a very dissected surface karst relief). The preservation of phreatic-lens related phenomena is rarely mentioned in association with this group (Szantner et al. 1986; Bárdossy & Kordos 1989; Esteban & Juhász 1990; Mindszenty 1991). On the *"underthrusting plate"* and along *transform margins* the role of karstification is more ambiguous. Phreatic-lens related and vadose phenomena may equally be abundant, apparently depending on the actual position of the depositional environment above base level of erosion.

Bauxites occurring in quiet **plate-interior settings** (low-lying coastal areas and islands) are invariably associated with complex, **phreatic-lens-related paleokarst** of the **early, diagenetic type** (pervasive dissolution, laminated, calcite-cemented cavity-fills as shown in Fig. 12). Features to be assigned to processes of the vadose zone are generally subordinate here with only shallow dolinas and a less dissected surface karst relief (D'Argenio 1963, 1966a, b; Carannante et al. 1974, 1987, 1992; Combes 1978; Vera et al. 1988; Boni & D'Argenio 1989).

One of the reasons for the difference regarding the relative abundance of vadose and phreatic lens related karst features in the two main settings is the fact that in the low-level plate-interior environment the chance for the development of a shallow phreatic lens and thus for the island-hydrological model to work is greater than in the tectonically uplifted, plate-margin areas. Also, we should remember that in areas subject to intense tectonic uplift, karstification goes hand-in-hand with erosion. Therefore, even if there were delicate mineral-controlled dissolution-features formed at early stages of the exposure, they would readily fall victim to erosion and subsequent water-controlled dissolution as uplift continues (see also Combes 1978).

4. Significance in the sedimentary cycle

4.1 Bauxites and stratigraphic gaps

Most bauxites, associated with mature paleokarst, occur in stratigraphic gaps the minimum duration of which falls generally between about 1 to 10 My. Whatever the actual duration of exposure is, this suggests that the formation of bauxites and related paleokarst phenomena requires long-lasting subaerial exposure, definitely longer than those resulting from high-frequency (Milankovitch-type) sea-level fluctuations and leading to recurrent brief episodes of karstification and soil formation. Paleosols associated with these high-frequency carbonate cycles are in fact only immature, slightly argillaceous weathering products rich in carbonate-silt which by far would not qualify as bauxites.

The actual **duration of exposure** is of particular importance. Unfortunately, direct dating of bauxites is an unsolved problem as yet. Being the products of subaerial weathering and generally of highly oxidized lithofacies, biostratigraphy can not be used to establish their age. Exceptionally, mainly in low-level settings, lignitiferous intercalations may provide enough sporomorphs and pollen to use palynostratigraphy as a tool. However, even in this way, we can only refine the upper limits of bauxite deposition and karstification, the duration of exposure will necessarily remain obscure (Combes & Peybernes 1987, 1991; Rákosi & Tóth 1980). Absolute dating may be of help only when bauxites contain sufficient amounts of unaltered primary silicates originating from contemporary volcanism (e.g. fission track dating of volcanogenic zircon grains from bauxites; Dunkl 1992).

Bauxite geologists generally interpolate between bedrock and cover by fixing the age of bauxite closer to the cover than to the bedrock (e.g., the charts of Bárdossy 1982). The idea behind this approach is that as long as climatic conditions are favourable and bauxites are exposed, bauxitization is an on-going process, brought to its end only by the deposition of the coverbeds. Although this approach may be justified, it still does not give any information regarding the actual duration of the subaerial phase. The core of the problem is that bauxites occurring in any gap represent only the "hiatus" but not the "vacuity", both of them being only fractions of the total gap[3]. In orogenically controlled areas the routine is to establish the age of the deformation responsible for subaerial exposure by using circumstantial geological evidence, to establish in this way the lower bound-

[3] terminology from Sloss 1963: **hiatus** is due to non-deposition, whereas **vacuity** is the result of erosion

dary of the hiatus. When bauxite deposits apparently associated with the same deformation are underlain by bedrocks of widely different age, the difference is ascribed to differential erosion controlled by topography (higher uplift → higher relief → higher rate of erosion → greater **vacuity** → greater total gap, even if the **hiatus** was the same). In addition to their effect on erosion, topographic differences may result also in diachronous burial, and therefore may influence the size of the hiatus as well (e.g. rising sea level would not reach highlands until after lowlands would submerge; D'Argenio 1963; D'Argenio et al. 1987). The issue would be even more complex when taking into consideration the diachronism of deformation itself (Sengör 1991; D'Argenio & Mindszenty 1991).

Another serious bias to establish the age of bauxites in orogeny-controlled areas is the possible merging of subsequent unconformities, like for instance in the Transdanubian Central Range of Hungary. There bauxites occur in three stratigraphic horizons (between Late Triassic and Albian, between Late Triassic and Senonian and between Senonian and Eocene). Supposed ages of the three bauxites are Albian, Senonian and Eocene, respectively (Dudich & Komlóssy 1969; Mindszenty 1984). However, in the case of bauxites occurring at the contact of Senonian and Triassic strata it is difficult to exclude the merging of the two older unconformities. There are several deposits sandwiched between Triassic and Eocene strata, where merging of all three horizons is very likely, too (Szantner et al. 1986; Mindszenty et al. 1994).

In plate interior settings the situation is generally less complex: relief is more even and stratigraphic gaps are usually much smaller. A better approximation of the hiatus is therefore possible by looking for the minimum gap within the area concerned. Even in this case, however, it should be born in mind that also the minimum gap consists of hiatus + vacuity and that to evaluate the hiatus properly needs further refinement.

One of the possibilities to refine the estimate is to use recent figures of carbonate deposition and karst denudation from analogous settings and calculate the probable duration of exposure from the total gap observed (Mindszenty et al. 1992, 1994).

An important constraint on the time issue is that from the pedological viewpoint, bauxites can be considered as the equivalents of present-day oxisols[4]. The minimum duration of exposure to attain oxisols is in the order of magnitude of 10^6 years (Birkeland 1984; Retallack 1990), a figure which can be used reliably as the lower age-limit when trying to estimate the age of any given bauxite deposit.

4.2 Bauxites/paleokarst – sequence boundary markers?

The first attempts to incorporate bauxites in the modern sequence stratigraphy concept were those by Esteban (1991) and Combes & Peybernes (1991). Of particular interest is the paper of Combes & Peybernes (1991) who, based on detailed analysis of bauxites of the Central Pyrenees (Ariège), put forward the idea of bauxite horizons to be correlated

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[4] oxisols = deeply weathered iron- and alumina-rich clayey soils with very low cation exchange capacity, predominant 1:1 clay minerals, very few weatherable primary silicates and a very particular micromorphology (spherical micropeds, iron/alumina concretions, etc.). Because of homogenization of the profile during the long timespan of soil development, horizonation is barely visible in oxisols. Their natural vegetation is rain forest. (US Soil Taxonomy 1992 and Retallack 1990)

with Type 1 and Type 2 unconformities (Van Wagoner et al. 1988) separating two 3rd order cycles within the Barremian to mid Albian sedimentary domain of the North Pyrenean shelf. In their interpretation the Transgressive Systems Tract (TST) would correspond to the deposition of lignitiferous clays and Urgonian limestones; the early Highstand Systems Tract (HST_1) spread argillites and pelites (future parent rock of bauxites) on the shelf, covered by a thin ferruginous glauconitic layer representing the Maximum Flooding Surface (MFS). Regression of the sea began with the late Highstand Systems Tract (HST_2) resulting in emersion and incipient ferrallitization of the exposed argillites. At the time of the deposition of the Lowstand Systems Tract (LST) in the basin, the shelf would have been completely emerged: karstification of the limestone substrate and bauxitization of the previously ferrallitized argillites took place.

This model of eustasy-controlled bauxite formation, though it applies very well for the low-level, low-relief setting of the North Pyrenean shelf, has, of course, no general validity. There are several other low-level bauxite deposits (e.g. in Italy or in Yugoslavia), where the effects of eustasy are either enhanced or overprinted by tectonism.

Based on their studies of Cretaceous bauxites of the Southern Apennines and Apulia, D'Argenio & Mindszenty (1992, 1994) suggested that the more or less simultaneous occurrence of bauxites in shallow-water plate interior settings at times of high eustatic sea level, would call for intraplate deformation, similar to the one proposed by Ziegler (1987, 1988). According to Ziegler, collision generated-stresses can be propagated towards plate interiors up to distances of 1300 kms, including uplift and wrenching of basement blocks. Jordan (1981), Cloetingh (1986) and Cloetingh & Worthel (1985) showed how compressive stresses may result in deformation of the elastic lithosphere. The order of magnitude of the phenomenon is calculated as a few tens of meters of uplift within areas of a few hundreds of kilometres apart (Cloetingh 1986). D'Argenio & Mindszenty (1992) proposed that such a mechanism may well explain the occurrence of Cretaceous bauxites within the interior of the Adria plate, subject to orogeny related deformation along both the Alpine and the Dinarid margins in Cretaceous times.

In this sense, bauxitiferous surfaces would correspond to exposure phases, related either to orogenically controlled angular unconformities (plate-margin bauxites and paleokarst), or to regional disconformities (plate interior bauxites and paleokarst).

Based on our personal experience mainly from Cretaceous bauxites of Hungary, Austria, the Southern Apennines, and to a lesser extent also from other bauxitiferous areas of the West Central Mediterranean (Southern Dinarids, Sardinia, Romania and Greece), we propose that the role of bauxites as sequence boundary markers should be treated with caution.

It can be accepted that bauxites, undoubtedly indicating subaerial exposure and concurrent erosion, compare very well with Type 1 sequence boundaries of Vail et al. (1984) and Van Wagoner et al. (1988), and that they should occur either at 1st and 2nd order supersequence boundaries, or at 3rd order sequence boundaries as suggested by Combes (1990), Esteban (1991) and Combes & Peybernes (1991).

However, most karst bauxites (and regional bauxite horizons) of the West Central Mediterranean ocurring at sequence boundaries, are associated **(i)** either with orogenically controlled unconformities characterized by stratigraphic gaps of 3 to 5 M years, or **(ii)** with plate interior carbonate-platform settings, where the gap is generally less than 3 M years. In this latter case, tectonic control is not so apparent, but all the same demonstrated by simultaneous subsidence and sedimentation in adjoining sectors of the same carbonate platform.

The evidence for tectonism playing such an important role in the formation of bauxites shows that even if – according to the geometry of the enclosing strata – bauxites and related "interregional" paleokarst do occur at major "sequence boundaries", not all of them would necessarily correlate with major **eustatically** controlled sequence boundaries shown on the Haq et al. (1987) curves.

In other words: bauxitic unconformities – even though generally marking regional emersion surfaces – may not fit into the classical concept of Type 1 sequence boundaries but rather should be qualified as tectonically enhanced (or even tectonically controlled) unconformities either of type 1 or type 2 sensu Jacquin et al. (1991).

Studies of Cretaceous successions of the Apulia carbonate platform (D'Argenio et al. 1986; Aiello 1992; Aiello & De Alteriis 1991; Mindszenty et al. 1994) show that in fact, at times of 3rd order sea-level highs there is karstification and bauxite deposition in the Murge/Gargano sector, whereas, at the same time, sedimentation continues not only in the surrounding basins but also on the adjacent shallow-water platform domains.

This close association of karst bauxites and tectonically controlled relative sea-level changes makes them good potential markers of *tectonics interacting with eustasy* in shallow-water carbonate sequences. Since the long duration of exposure results in substantial alteration of the carbonate substrate, bauxite-filled paleokarst surfaces can easily be detected also on well logs and seismic profiles (Nyerges & Mindszenty 1979; Del Olmo & Esteban 1983; Esteban & Klappa 1983; Fontaine et al. 1987).

5. Relationships to climate and eustasy

5.1 Bauxites and climate

As it was already cited above, there is a general agreement, based mainly on Tertiary to Recent analogues from laterite-covered terraines of the intertropical zones, according to which karst bauxites are the fossil equivalents of present oxisol-type weathering products. Like their recent lateritic counterparts, karst bauxites are also the products of humid warm climates. Periods of the Earth's history when karst bauxites were particularly abundant are therefore considered to have been globally warm and humid. Nicolas & Bildgen (1976), Bárdossy (1973, 1982, 1986) and others have pointed out that the paleogeographic position of karst bauxites suggests that they preferentially occur on the windward side of continents influenced by monsoon-type atmospheric circulation. Though, theoretically, bauxite formation in the intertropical zone may be possible even at times of global cooling, the distribution of bauxites through time clearly shows that their maximum areal spread corresponds to periods of global warming (e.g. in Cretaceous/Early Tertiary times we find bauxitic clays as far to the North as Ireland, Bárdossy & Dercourt 1990).

Intense weathering and soil formation under warm humid conditions in densely vegetated tropical terraines necessarily results in the transport of large quantities of dissolved nutrients and fine colloidal terrigeneous organic matter into the oceans. High temperature and abundant nutrients being generally considered to be the key factors in increasing the organic productivity in the photic zone of the oceanic reservoir as well, it is very

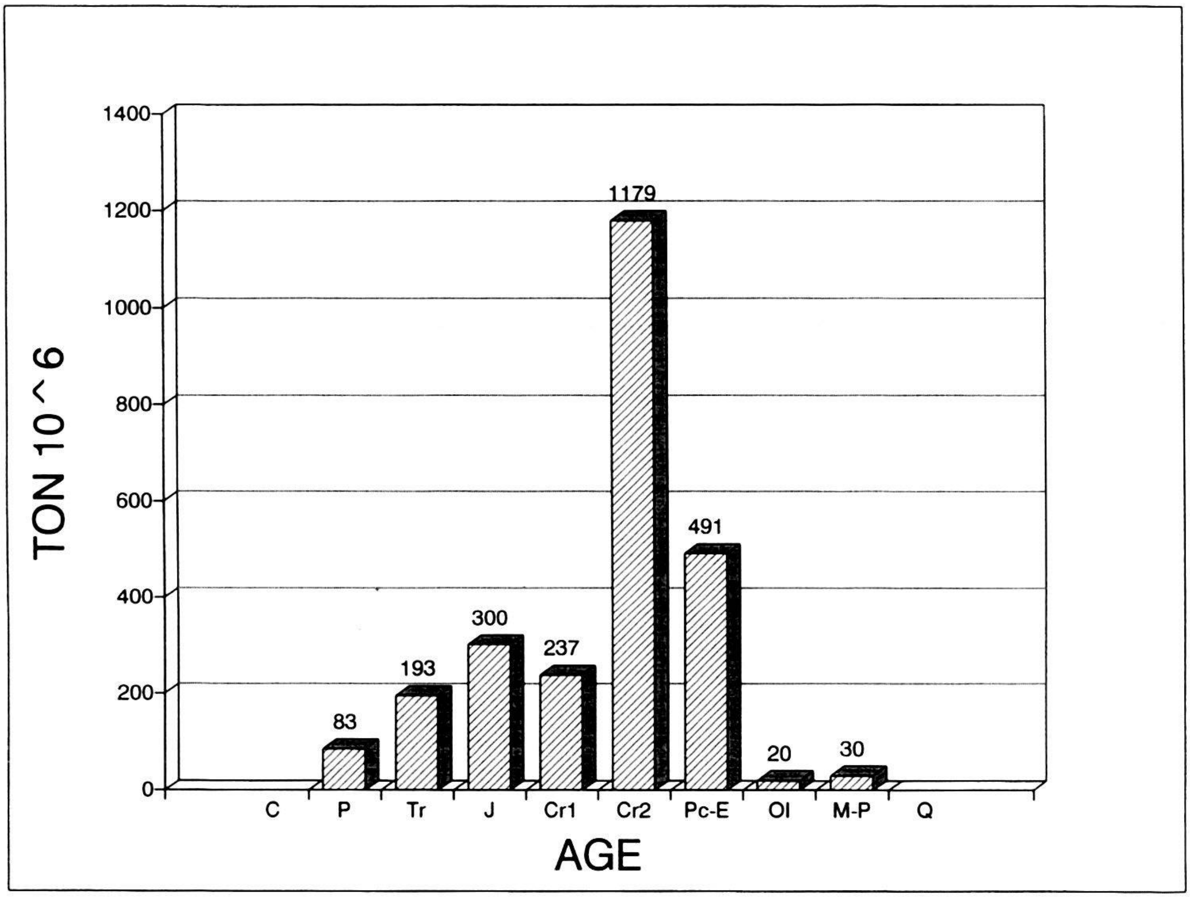


Fig. 19. Tonnage versus time of Phanerozoic Mediterranean karst bauxites, in 10^6 tons (data from Bárdossy 1982).

likely that under warm climatic conditions terrigeneous influx in shallow pericontinental areas may remarkably increase the organic "load" of the ocean.

In globally warm periods, like for instance in Cretaceous times, when the intensity of terrestrial chemical weathering is globally increased and the increase is recorded by exceptional abundance of bauxites, the associated terrestrial influx (both fine particulates and solutes) into the oceans may play a decisive role in the development of anoxia on the regional scale (D'Argenio & Mindszenty 1992) (Fig. 19). Chemical analyses of Mid Cretaceous sediments from the Atlantic corroborate this idea: in many anoxic layers organic matter proved to be of predominantly terrigeneous origin (Petters & Ekweozor 1982; Simoneit 1986).

The idea of a causal link existing between periods of intense chemical weathering on the continents and increased organic productivity in the oceans, concomitant with globally high sea-levels, is not new. Following Erhart's "biostasy" (1956, 1966) and Fischer & Arthur's "polytaxic" times (1977), Föllmi et al. (1993) recently introducted the term VITAMIN periods for time intervals characterized by increased precipitation and runoff, eustatic sea-level rise and intensified upwelling in the oceans. They suggested that VITAMIN periods should correlate with phases of increased laterite and bauxite formation.

We think that the distribution of Phanerozoic bauxites supports the suggested causal relationship. Tentative correlation of bauxites and anoxic sediments shows that, on the large scale, a reasonably good fit is possible at the time of the Cretaceous "greenhouse", when both bauxites and anoxic sediments reach their maximum abundance (Fig. 20, 21).

Detailed correlation at the scale of third- (or higher) order relative sea-level changes is, however, problematic (Bernoulli & Weissert 1991). One of the reasons for the unsatisfactory fit may be the different accuracy of the available stratigraphic data. Quite naturally, direct dating of anoxic sediments in pelagic environments provides for much greater precision than the indirect dating of bauxites occurring on exposed shallow platforms. Possible reasons for the unsuccessful correlation may be that **(i)** bauxites, instead of being strictly coincident with the anoxic events probably **precede** them (they are the manifestations of that intense tropical weathering which releases nutrients and terrestrial organic carbon into the oceans), and **(ii)** climate is only one of the controlling factors in bauxite formation. In fact, as we have shown above, tectonics is of overall importance in controlling bauxite formation. Thus, even though the general abundance of bauxites is apparently greatest at times of optimum climatic conditions ("greenhouse"), their actual stratigraphic position within the given climatic optimum "window" is determined by the timing of the tectonic events which eventually provide for subaerial exposure within the favourable (humid) climatic zones. The association of bauxites with tectonically controlled unconformities thus may preclude precise correlation with eustatically controlled sea-level fluctuations shown to be responsible for Oceanic Anoxic Events (Jenkyns 1980; Weissert et al. 1979).

Notwithstanding the difficulties of direct correlation, we suggest that bauxites and Oceanic Anoxic Events are causally related phenomena. Though both are likely to be the expressions of the greenhouse, we think that they are not only passive products of climate warming but two links in the chain of feedbacks developed to counteract the climatic perturbation. In this context bauxites may be considered as terrestrial fore-runners of black-shales, developing *before* anoxia becomes wide-spread in the oceans, and actively contributing to the overturn of the oceanic ecosystem. Additional research to reveal further details of this relationship should focus on bauxites occurring in relatively small stratigraphic gaps (in passive plate interiors), because in such settings time-resolution may be better than in case of the plate-margin deposits.

5.2 Bauxites and eustasy

Erhart's theory on biostasy/rhexistasy (1955, 1967) was rather explicit about the correlation of periods of intense chemical weathering with a generally high base-level of erosion and warm humid climate (the equivalents of sea-level highs). It was confirmed also by Damon (1968) who argued for a strong correlation between high sea-level and warm climates. However, by the seventies, when the construction of global sea-level curves by Vail et al. (1977) offered the first opportunity to see whether the distribution of bauxites in time could be fit to eustatic events, Erhart's ideas became apparently forgotten. As a result of the few attempts to correlate bauxites and/or extensive paleokarst with eustatic sea-level changes (D'Argenio 1970; Bárdossy et al. 1977; Combes & Peybernes 1989, 1991; Bárdossy & Dercourt 1990; Combes 1990; Bernoulli & Weissert 1991; Esteban 1991, and others), a general consent about regional bauxite/paleokarst horizons probably

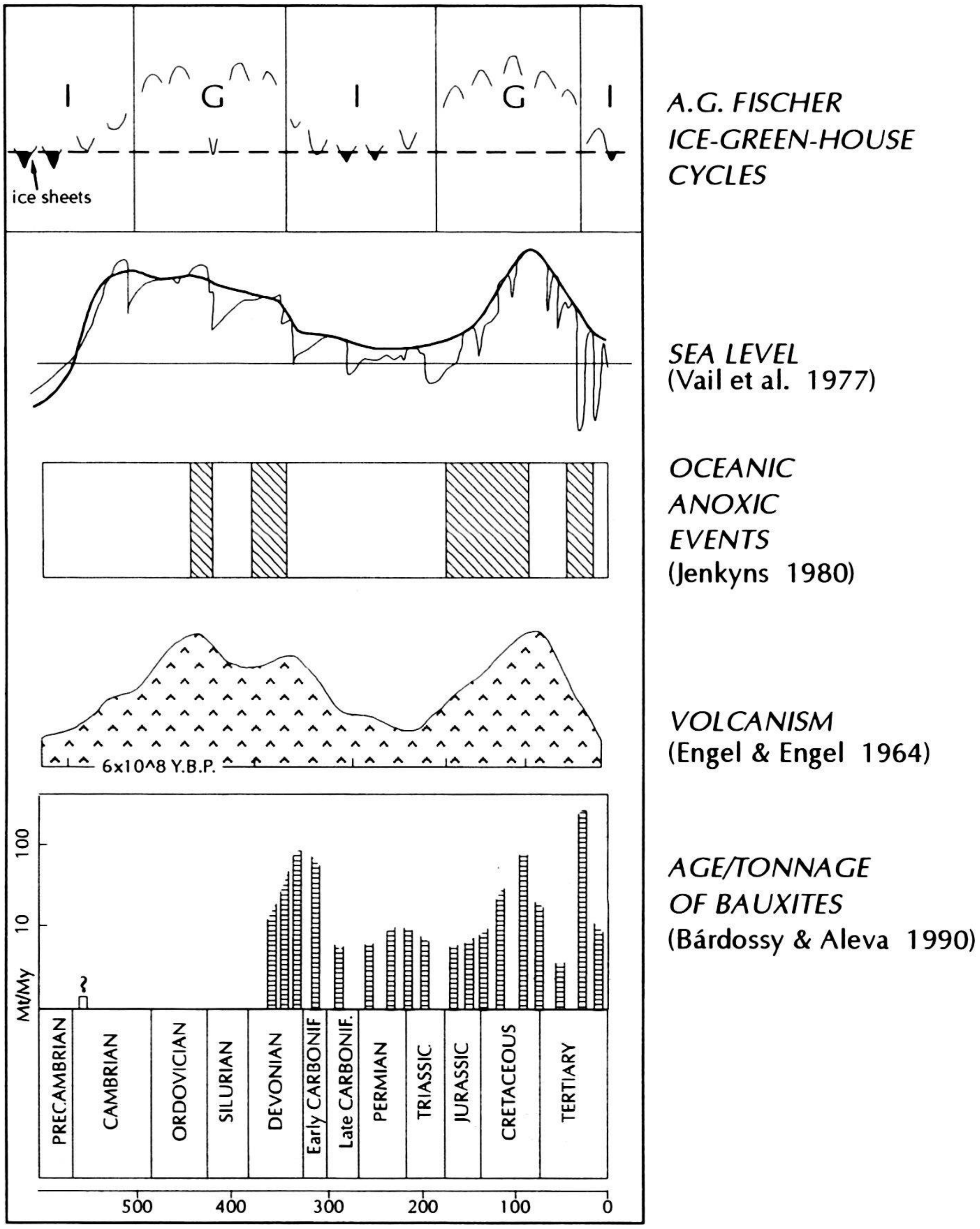


Fig. 20. Estimated reserves of world karst bauxites (in 10^6 tons) and contemporaneous global events. Note the clear correlation of volumes of bauxites with peaks in volcanic activity (as inferred from volumes of North American plutonites) and Oceanic Anoxic Events, first (and sometimes second) order peaks on the "Vail" curves and A. G. Fischer's Green House Times. Due to their young age and hence preferential preservation, late Tertiary to Quaternary bauxites are not considered here (they are not yet "normalized" by erosion). Age and tonnage of bauxites (numerical data) from Bárdossy & Dercourt (1991), volcanism from Engel & Engel (1964, fide Fischer 1981 and reference therein), Ocean Anoxic Events from Jenkyns (1980), global sea level oscillations from Haq et al. (1987), Green House – Ice House Cycles from Fischer (1981).

associated with global sea-level falls became established. That this is not always the case, was shown by D'Argenio & Mindszenty (1987, 1991). Having analysed the distribution of Cretaceous bauxites and related paleokarst occurring in distal carbonate platform environments of the Mediterranenan they concluded that most of those bauxites/paleokarst were formed at times of high eustatic sea-level and reflected periods of tectonic deformation (and related subaerial exposure), rather than short-lived relative sea-level falls shown on the Haq et al. (1987) curves.

Considering the largest 3rd order fall on the Cretaceous sea-level curve (89 My, Coniacian, Haq et al. 1987) when essentially all the shallow water platform areas of the Adria plate should have been exposed, it is striking to see, that, although there are bauxites to correlate with this fall, most of the platform was still under water.

Esteban (1991), on the other hand, based on the analysis of 254 case histories including bauxitic and non-bauxitic paleokarst horizons concluded that *"eustatic control in karst development is predominant"*, and karst porosity is essentially created through sea-level drops, though he admitted that "tectonic control and associated fracture networks are commonly involved in it".

Our studies of Cretaceous bauxites and related paleokarst in the West Central Mediterranean suggest the necessity of a more complex approach. We have already shown that the two essential prerequisites of bauxite formation are subaerial exposure and humid tropical climate. Now we propose that the distribution of bauxites (and related paleokarst) is a result of a double – tectonic and eustatic – control, in the sense of globally high sea-levels providing for the necessary wet and warm climate and tectonic deformation accounting for subaerial exposure within the appropriate climatic zones. In other words – as pointed out in chapter 4.2. –, tectonics, instead of just modifying the effects of eustasy, are a major controlling factor. The influence of eustasy – opposite to what might be expected – is much more important from the point of view of the climate than from that of the actual exposure.

As to paleokarst, we think that eustasy-related climatic configuration also is of utmost importance. Intense karstification needs ample quantities of meteoric water plus copious biological activity. Both these key factors may be more efficient in warm than in cool periods. Thus, we may expect that optimum conditions for extensive deep paleokarst horizons to form are realized at times of globally warm humid climate (coincident with global high-stands of sea-level) in areas where long-lasting subaerial exposure is provided by tectonism within a suitable climatic zone. In non-glacial times, without the contribution of tectonics, eustatic falls of sea-level are probably not large and not long enough either to create sufficiently thick vadose zones where cavity formation may outrank cementation (prevalent in the phreatic zone). To confirm this rather indirect conclusion, we would need a detailed revision of all the pertinent data – which of course is beyond the scope of the present paper.

6. Role of volcanism and tectonics

6.1 Bauxites and volcanism

Direct evidence of volcanism contemporaneous with bauxite formation in the Tethyan realm is sparse, even though the possible role of pyroclastics in providing the necessary source material for bauxites has often been referred to in the literature (Maric 1966; D'Argenio 1970; Bárdossy et al. 1977). One of the reasons why the identification of volcanic material in bauxites may be difficult if not impossible is that bauxitization is an intense and complex geochemical process (by far not all the details of which are understood), involving efficient selective leaching of all elements soluble under humid tropical conditions. Fine-grained pyroclastics, particularly vulnerable in environments like that, are the first to yield, so that generally only the few resistant components (like zircon, ilmenite or apatite) have a chance of survival.

The few direct evidences of volcanic contribution, mainly extraclasts (minor rock fragments or single mineral grains) recovered from the HCl-insoluble residue of bauxites and studied by micromineralogical means, invariably point to acid to intermediate chemical composition of the source (Vörös 1958; Bárdossy et al. 1977; Mindszenty et al. 1991; Trubelja 1991; Dunkl 1992). Of particular importance in this respect is the work of Dunkl (1992), who, on the basis of morphometry and fission-track dating of zircons from early Tertiary bauxites of Hungary, proved that contemporary explosive volcanism was certainly one of the major material contributors to the formation of those bauxites. The geochemical signal of eventual volcanism is generally obscured by the obviously polygenetic nature of the bauxitic sediment: trace elements derived from eroded sedimentary, metamorphic and igneous rocks of various (ophiolitic to calc-alkaline) composition and transported to the carbonate terrain in dissolved or particulate form do not permit the separate, geochemistry-based identification of volcanic contribution in the bauxitized end-product (Schroll & Sauer 1964; Özlü 1983).

Despite the scarcity of direct evidence, however, there are a number of additional arguments strongly suggesting that the role of volcanism in bauxite formation should not be underestimated.

There are workable bauxite reserves known from isolated carbonate platform environments and underlain by biogenic shallow-water carbonates, the dissolution residue of which is obviously inadequate to account for the amounts of bauxite formed. The amount of bauxites in such settings is inexplicable unless supposing some extraneous source material. One may very well speculate that the volume of air-born dust episodically became enhanced by explosive volcanic activity and was coincident with the exposure of the carbonate terrain.

As for an example let us recall the case of the Southern Apennines where carbonate sedimentation was repeatedly interrupted by subaerial exposure. However, bauxite deposits are associated only with one of the paleokarst horizons thus created. Those underneath and above are filled only by red-coloured calcilutites or, when postdating the bauxitiferous horizon, every now and then also by reworked and redeposited bauxites. The conclusion that the principal bauxite horizon is the product of the coincidence of subaerial exposure and some extra material-supply (possibly by contemporaneous though distant volcanism) is temptating in this case and was already suggested by D'Argenio (1969) and Bárdossy et al. (1977).

Evidence of volcanic activity contemporaneous with the estimated stratigraphic position of Tethyan bauxites is scarce, but the few available data fit quite well with the major "bauxitic" periods (e.g. pyroclastic intercalations in the Tolfa Flysch in Late Cretaceous times reported from the Appennines by Di Girolamo et al. (1984), or bentonites from the Late Cretaceous Gurnigel Flysch (Central Alps) described by Bernoulli & Winkler (1990).

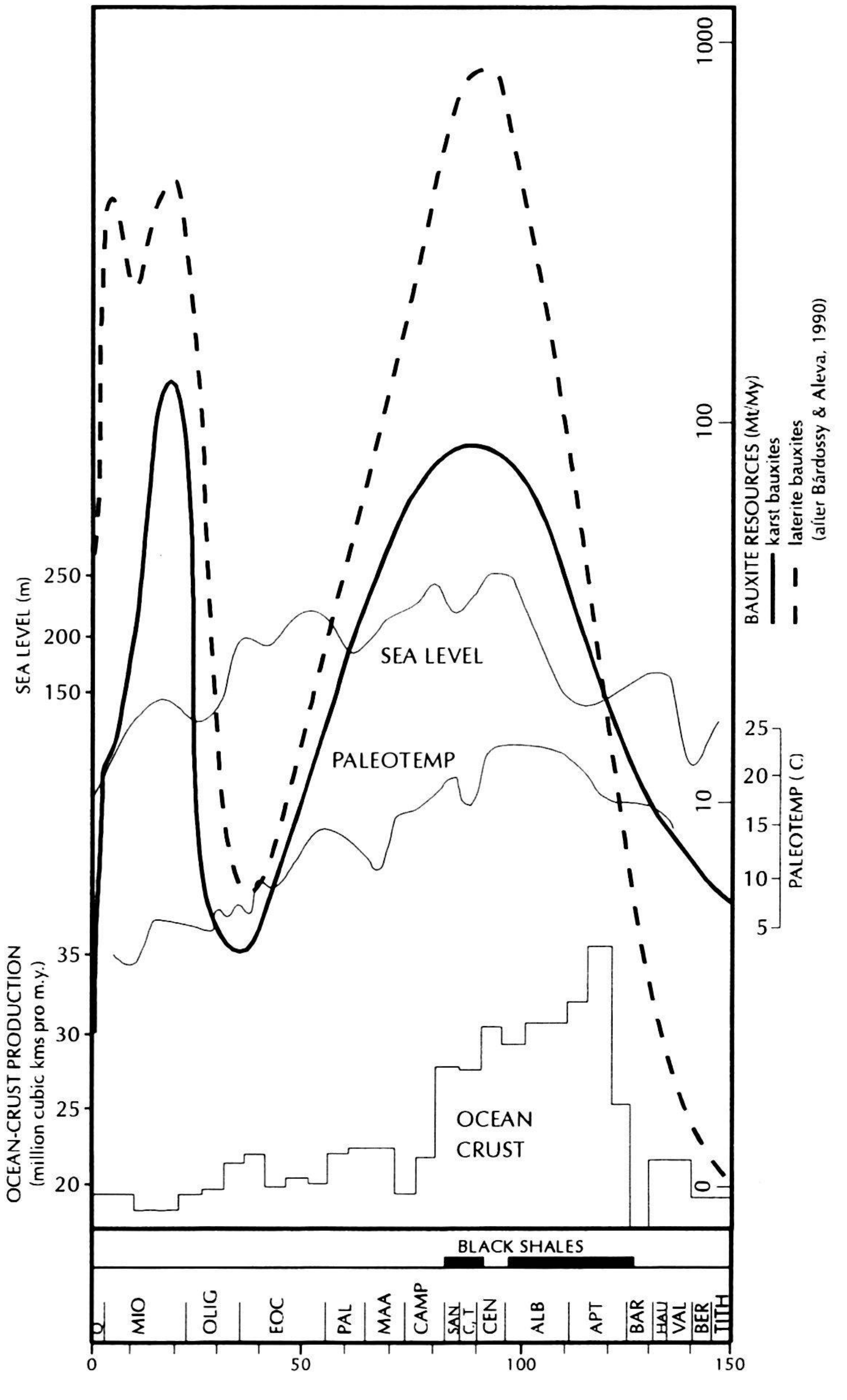


Fig. 21. Cretaceous-Tertiary tonnage of karst and laterite bauxites vs time (after Bárdossy & Aleva 1990) combined with the ocean crust production vs time curve of Larson (1992) and with sea-level changes, paleotemperatures and black shales. It is worth noticing the coincidence of bauxitic peaks with sea level and paleotemperature oscillations as well as with peak abundances of black shales.

Periods of intense world-wide volcanic activity, when plotted against the curve of long-term sea-level variations, show a very good agreement with 1st order global sea-level highs (Fischer 1981). As it was shown above, bauxites also preferentially occur at times of high sea-level so consequently they do correlate with the peaks of volcanism as well (Fig. 20, 21).

For a long time it has been widely accepted that volcanism enhancing the amount of atmospheric CO_2 may be one of the major factors in triggering periods of global warming, culminating in the "Green House" mode of the Earth (Fischer & Arthur 1977) characterized by high sea-level and warm, humid, equable climates (the prerequisites of intense chemical weathering karstification and eventual bauxite formation on land). Recent calculations by Rampino (1991) and Caldeira & Rampino (1990), however, showed that the perturbation of atmospheric CO_2 at times of intense volcanic activity would not have been able to warm the Earth more than about 1 °C over a period of a few hundred thousands years (and this would have been about the order of magnitude of the relaxation time to return to steady state CO_2 value again). Whether it was the ultimate reason for global warming or just an accompanying phenomenon, excess atmospheric CO_2 is considered as one of the most important attributes of the greenhouse, capable to intensify chemical weathering on land, even if temperature was moderate.

So, the correlation of bauxites (and related paleokarst) with peaks of volcanism may very well be the consequence of the impact of volcanism on sea-level and climate which then directly control the intensity of bauxitization/karstification. Sea-level rise and peak intensities of volcanism were suggested to be related to periods of intense plate tectonic activity (Hays & Pitman 1973). This way the anomalous abundance of bauxites simply could be the consequence of the coincidence of volcanic CO_2-related climate warming and increased humidity (the latter resulting from the maritime effect of high sea-levels). The correlation between bauxites and volcanism may not be primary but indirect, via high sea-levels and climate warming.

On the other hand, inasmuch as explosive volcanism is considered as one of the major material-supplier for many bauxites, the correlation may work also directly by the deposition of fine-grained volcanic ash on the exposed carbonate terraines.

6.2 Bauxites and tectonics – a reappraisal

As it was shown, the relationship between bauxites and **regional tectonics** is obvious in **orogenic areas**, where

(i) uplift and consequent subaerial exposure is brought about either directly by inverse faulting, overthrusting, nappe tectonics or indirectly by the tectonic load of the advancing nappes – resulting in peripheral (or flexural) bulges;
(ii) karstification is fracture-controlled, and
(iii) resedimentation of bauxite, and also subsidence and burial of the deposits thus formed, is tectonically controlled.

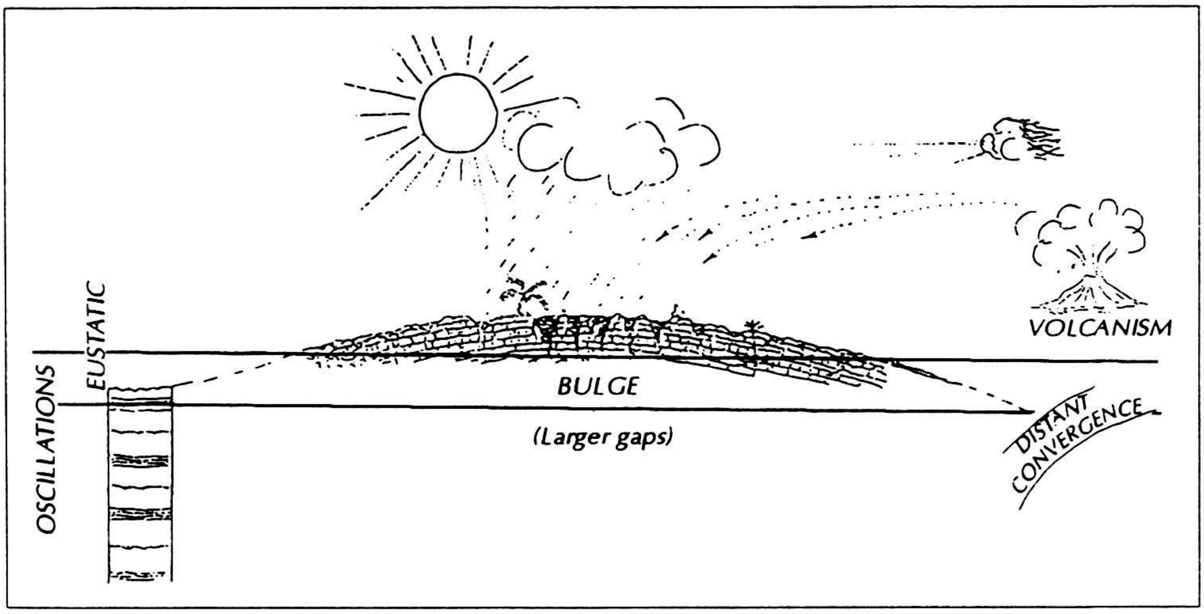


Fig. 22. Cartoon illustrating the tectonically controlled nature of karst bauxite formation. Cloetingh's (1986) model for distant lithospheric bulges of "passive" plate interior areas, with the resulting bauxites and paleokarst (when uplift takes place at times of humid tropical climate and when sufficient source material is available). Preceeding the bulge-related exposure, cyclothemes develop on the future bauxitiferous area. During bulge-times cyclothemes are restricted to the adjoining non-exposed sectors of the platform.

The relationship, although more obscure in "tranquil" **plate-interior areas**, is clearly shown

(i) by the timing of bauxitic episodes in plate-interior settings, which seems to correlate with orogenic events taking place along the distant margins of the same plate, and

(ii) by the morphofacies and the lateral facies relationships of bauxite, which often point to tilting of the substrate possibly associated with intraplate-stress induced lithospheric arching.

Therefore even in these cases tectonism was suggested to outrank or at least modify/enhance the role of eustasy in providing the necessary subaerial erosion (Fig. 22).

The effect of **global tectonics** on bauxites is twofold:

(i) Time/space distribution of bauxites over subaerally exposed parts of any given continental plate is certainly determined by the position of that plate as related to the paleoposition of the intertropical zone – offering optimum climatic conditions for bauxite formation. Collision zones, particularly those of the continent/continent configuration, are considered as favourable, because they provide optimum conditions for both material supply (erosion of highly-uplifted segment, subduction- or strike-slip related volcanism) and deposition (exposed terraines) (cf. with Bárdossy 1973, 1982).

(ii) The position of rifting zones relative to the intertropical belt in the early stages of a Wilson-cycle may control the extension of carbonate terraines – the recipients of karst bauxites formed as a result of later orogenic events: E-W oriented rifting zones in the intertropical belt necessarily result in the formation of huge shallow carbonate platforms (as was the case in the Mesozoic Tethys) which later on, by exposure and karstification, serve as optimum substrates for bauxites (cf. Mediterranean/Tethyan example).

7. Bauxites as event markers

Having analysed the relationship of bauxites and the accompanying paleokarst features with the enclosing rocks, and with contemporaneous climatic, eustatic, tectonic and volcanic events we come to the conclusion that their occurrence is controlled by the coincidence in time and space of a very particular configuration of the above factors. Figures 19 and 20, the latter incorporating relevant information also on all known karst bauxite deposits of the world, seem to justify the generalization that karst bauxites can be considered as **regional markers of global events**. Their abundant occurrence in certain intervals in the stratigraphic record indicates the coincidence of favourable climatic conditions with tectonically controlled exposure of extensive actual or former carbonate platform areas and with peak intensities of explosive volcanism.

Global factors in triggering bauxite/paleokarst on the "event"-scale are climate and eustasy (first and second order cycles). Warm climate combined with humidity (a general attribute of globally high sea-levels) provides for the predominance of chemical weathering over mechanical erosion on land (see Erhart's "biostasy" or Fischer's "greenhouse"). Since bauxite formation needs not only warmth but also humidity, it is quite clear that even at times of greenhouse warming there will be climatic zones where bauxite formation will be inhibited by the lack of sufficient rainfall. Still, we think that the total extension of humid **and** warm climatic zones was greater at greenhouse- than at icehouse times.

The northward shift of the summer rain (monsoon) belts in Africa and Asia at the time of the early Holocene warming (Ritchie & Haynes 1987, Mc Kenzie 1993) offers a good analogue to rely on when speculating about the effects of climate warming in Mesozoic times. General Climate Models are, however, rather equivocal about precipitation changes. Model-data discrepancies, particularly those in tropical areas, were discussed extensively by Crowley & North (1991). We think, that bauxites – at least in those periods when they were particularly abundant – may reliably be used to indicate the extension of humid and warm climatic zones on the continents.

The regional factors controlling the actual manifestation of the "event" are tectonics and volcanism which provide for exposed land surface in the most favourable climate zones and enhance the amount of easily weatherable source material deposited on the exposed areas.

When tectonics (be it compressive or distensive) results in exposure on the local scale, at places where the prerequisite of optimum climatic conditions is fulfilled (e.g. Jurassic bauxites in Spain, or Sicily on locally exposed parts of rotated blocks of the subsiding carbonate shelf as described by Vera et al. (1988)), a **Local Karst Bauxite Event** (LKBE) occurs.

When the tectonic prerequisite for maximum exposed carbonate terrain (e.g. continent/continent collision) is fulfilled and coincides with a global climatic optimum ("greenhouse"), a **Global Karst Bauxite Event** (GKBE) occurs.

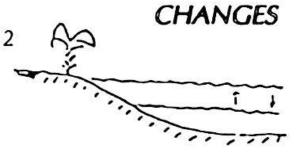
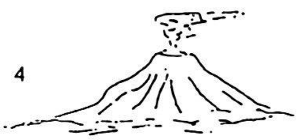
CONTROLS ⇒	PROCESSES ⇒		RESULTING ROCKS
CLIMATE 1 	WARM HUMID (Green-house)	BAUXITIZATION AND ITS DIAGENETIC OVERPRINTS	"VADOSE" & "PHREATIC" BAUXITES
SEA LEVEL CHANGES 2 	HIGHER FREQUENCY OSCILLATIONS	Minor Karst solution	MINOR PALEOKARST (in cyclic sequences)
	LOWER FREQUENCY OSCILLATIONS	Sea Level Higstands (if coupled with Tectonics) ?Biostatic times Sea Level Lowstands (coupled or not with Tect.) ?Rhexistatic times	KARST BAUXITE (& black shales at sea) NON BAUXITIFEROUS KARST
TECTONICS 3 	FAULT & THRUST RELATED UPLIFT OPHIOLITE EMPLACEMENT LITHOSPHERIC ARCHING	Subaerial Exposure of Appropriate Bedrock Erosion (rate of) Production of Parent Material (surface transp., mostly)	BAUXITIC DEPOSITS ON ATTACHED/DETACHED CARBONATE PLATFORMS
VOLCANISM 4 	EXPLOSIVE VOLCANISM (mostly) & PYROCLASTICS	PRODUCTION OF PARENT MATERIAL (wind blown, mostly)	BAUXITES ON DETACHED CARBONATE PLATFORMS

Fig. 23. Main controls on karst bauxite formation (modified after D'Argenio & Mindszenty 1992).

Particularly favourable plate tectonic configurations (exposed cratons and continent/continent collision along East-West oriented convergence zones in the Intertropical Belt) at times of global climatic optimum may result in **World Wide Bauxite Events** (WWBE) characterized by contemporaneous abundance of lateritic and karst-related bauxites (e.g. the Cretaceous or the Miocene). At times of WWBEs, bauxites can be used as another proxy indicator of the extension of warm and humid climatic zones (particularly when independent evidence on their paleoposition is available).

It has to be recalled that though karst bauxites are invariably accompanied by paleokarst phenomena, not all regional paleokarst horizons are necessarily bauxitiferous (cf. Esteban & Klappa 1983; Esteban & Juhász 1990; James & Choquetta 1988, and others). We suggest that non-bauxitic paleokarsts – potential hosts for other economic mineral resources, like Mississippi-valley type Pb-Zn deposits or hydrocarbons – indicate that the contribution of one or the other of the above mentioned factors failed to reach the level required for a bauxite event. This "mismatch" may be realized in time or (locally) in space. Subaerial exposure by tectonism at times of minor explosive volcanic activity, coincident with a global lowstand of sea-level and the consequently less warm climate may create deep regional to interregional paleokarst horizons which, in lack of abundant tropical weathering products, will not be filled up by bauxite ("time-mismatch"). On the other hand, at times of global highstand of sea level when the coincidence of climatic and tectonic factors provides for exposure and intense dissolution at places distant or protected from pyroclastic influx and subject to local aridity (e.g. west-facing continental margins at times of monsoonal atmospheric circulation), again "empty" paleokarst may form, though only on the local scale ("space-mismatch").

Bauxite-filled karst on the event-scale occurs only when the coincidence of all four factors provides for the prevalence of optimum climatic conditions over maximum extension of subaerially exposed carbonate terrains, and at the same time for optimum material supply as well.

On the contrary, **non-bauxitic paleokarst** develops at times of eustatically and/or tectonically controlled exposure when climate is not sufficiently hot and humid to produce bauxites which would efficiently occlude the created porosity.

Thus bauxitic and non-bauxitic paleokarsts apparently are mutually exclusive in time (but not necessarily mutually exclusive in space as well).

8. Conclusions

(i) Bauxites in general and karst-bauxites in particular are **"fashion-sediments"** occurring episodically during the Earth's history when the coincidence of particularly favourable greenhouse-type climatic conditions with a likewise favourable tectonic configuration allows for the optimum of chemical weathering (exceeding the rate of mechanical erosion) and for the maximum extension of exposed land to serve as the source and the recipient for the weathering products.
It is suggested that the coincidence of these "fashion sediments" with other well-constrained events (e.g. anoxia in the basins and on the shallow platform areas, volcanism, high sea-level) justifies their qualification as **event-markers**.

(ii) Bauxitic paleokarst (be it local or regional) may contribute to the understanding of the anatomy of an unconformity:
- The relationship of bauxite to its bedrock (angular unconformity or simple disconformity/paraconformity) is a tale-teller of processes which brought about the unconformity (style of tectonics and the relationship between tectonic and eustatic processes producing the stratigraphic gap).
- The study of paleokarst features, when combined with the geochemical/lithological facies of the associated bauxite, may help to estimate the relative paleo-altitude of the exposed terrain. Lateral facies relationships and their anomalies may reveal subtle tectonic processes (= gentle tilting, arching) having affected the bauxitiferous area during the accumulation of bauxites.
- Extraclasts recovered from the micromineralogical residue of bauxites may help to speculate about contemporaneous volcanism and the geology of adjoining exposed non-carbonate terrains, and eventually facilitate the analysis of their denudation history.

- Lithological/geochemical changes within the same bauxite deposit may reveal subtle climatic/eustatic/tectonic changes having taken place during the subaerial exposure phase.
- The relationship between bauxite and its cover records the rate and style of subsidence after the subaerial exposure phase.
- So, the history of a **local karst bauxite event** is recorded in the complex interrelationship between bauxite, its substrate and its cover.

Quite naturally, to understand the **complete history** of a **global karst bauxite event** would require more information. In addition to the critical assessment of all bauxites belonging to one and the same event, also contemporaneous **non-bauxitic paleosols** and **non-bauxitic paleokarst** features should be systematically reviewed. Only in this way climatic information will be complete, and the development and waning of the event properly understood.

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