



Characterisation of selected bauxite profiles in Slovenia with emphasis on REE distribution

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ABSTRACT

Bauxites are the primary mineral resource for alumina and aluminium production. Recently, there has been growing interest in the chemical characterisation of bauxite, as it is listed as a critical raw material (CRM) by the European Union and can contain elevated content of rare earth elements (REE), which are also listed as CRM. This research focuses on the REE content and distribution across profiles of four Slovenian bauxite occurrences of different ages (Triassic T_3^{2+3} , Jurassic $J_3^{1,2}$, Cretaceous $K_2^{2,3}$ and Oligocene Ol_2) and their implications for potential genesis. General mineral composition analysed by XRD showed a prevalence of böhmite and kaolinite in all samples except Ol_2 , where diaspore is the main Al-hydroxide. Minor minerals include hematite, quartz, and anatase. Geochemical ICP-MS analysis showed the lowest REE content in Cretaceous bauxites (average 218 mg/kg) and the highest in Jurassic bauxites (average 711 mg/kg). SEM/EDS inspection revealed different carriers of REE. The main carriers of REEs in all profiles are mostly detrital, with some individual secondary authigenic xenotime, secondary authigenic cerianite (Ce) (T_3^{2+3} , $J_3^{1,2}$), calcioancylite (Nd) or cerianite (Ce) without Th ($J_3^{1,2}$, Ol_2), lanthanite (Ce) and (Nd). Relatively low P_2O_5 indicates dispersion of REEs throughout a profile and their adsorption onto Al/Fe oxides and hydroxides and clay minerals. The T_3^{2+3} , $J_3^{1,2}$ and $K_2^{2,3}$ bauxites show a changing Eh-pH environment, which supports their categorisation as vadose bauxites, while the Ol_2 profile is phreatic bauxite where redox conditions prevailed.

1. Introduction

Bauxite is a residual sedimentary rock composed of at least 50% aluminium, iron and titanium oxides and hydroxides, with aluminium minerals being the most abundant (Bárdossy, 1982). It mainly consists of böhmite, gibbsite and diaspore, with smaller amounts of iron oxides and hydroxides, as well as minerals such as quartz, rutile and kaolinite. Due to its high content of aluminium oxides and hydroxides, bauxite can be economically processed to alumina using the Bayer Process; therefore, bauxite is the main ore of aluminium (Gow and Lozej, 1993). Bauxite and aluminium have been listed as Critical Raw Materials (CRM) for the European Union since 2021 (European Commission, 2020, 2023). CRMs are materials of high economic importance for strategic technology sectors (renewable energy, e-mobility, energy production, digital technology, space, etc.) and are subject to high supply risks, combined with low recycling rates and limited possibilities for substitution (Hollis et al., 2025). In addition to being listed as a CRM itself, bauxite also contains a variety of minor and trace elements that can be of economic importance and are also included on the CRM list – for instance, Ba, Be, Bi, Co, Ga, Hf, Nb, Sc, Sr, Ta, Th, Ti, V, W, and Light and Heavy Rare Earth Elements (LREE and HREE) (Liu et al., 2013).

Bauxites can be divided into lateritic and karst bauxites. Lateritic bauxites are formed by the lateritic weathering of silicate rocks in tropical climates. They are characterised by large deposits with relatively homogeneous structures that can extend continuously over large areas or even regions. Karst bauxites are found on carbonate rocks in lenticular or pocket deposits, as accumulations of weathered material trapped in karst palaeo-relief (Bárdossy, 1982; Mongelli et al., 2014). Karst bauxites are generally more enriched in REE than lateritic bauxites because they are composed of different source materials (insoluble limestone residuum, eolian silt, clay and volcanic ash, and weathered products of surrounding rocks) and develop under alkaline conditions, which promote REE stability (Mordberg, 1993; Pajović, 2009; Abedini et al., 2021). The REE content can vary significantly throughout the profiles, but it usually increases with depth due to bauxitisation and the formation of authigenic REE minerals (Deady et al., 2014).

Bauxites can be used to study the palaeogeographical and palaeo-environmental evolution of regions. U-Pb geochronology of stable minerals can reveal the time spans of deposition of the bauxite protolith as well as their source rocks (Kelemen et al., 2023; Bilić et al., 2025). Transportation paths and directions can also be reconstructed. Bauxites may contain pollen and microfossils, which support dating and

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environmental interpretations (Yang et al., 2022). The mineralogical and geochemical composition of bauxites indicates diagenetic, hydrothermal, and supergene processes. This also reflects the environment in which bauxites formed and the dominant bauxitisation processes (Zhao et al., 2023). These parameters, especially geochemical ratios such as Ni-Cr and Sm/Nd-Eu/Eu*, can be used to infer the parent source rocks (Radusinović et al., 2017; Tomašić et al., 2021). Several processes and factors contribute to the enrichment of bauxites with REE (Maksimović and Panto, 1991). Geochemical profiling combined with SEM/EDS analyses may reveal the REE carriers and the processes influencing their distribution. Different REE carriers affect the possibilities and methods of extraction (Wang et al., 2010; Li et al., 2013).

Due to the growing global demand for REE and other CRMs, research on bauxite and red mud – the bauxite residue from the Bayer process – has increased in recent years. Many bauxite research focuses on the mineralogical and geochemical characteristics of bauxite deposits within diverse lithological units, as well as the content and distribution of REE and other CRMs (Brlek et al., 2021; Ahmadnejad et al., 2017; Mondillo et al., 2022; Zhang et al., 2022; Sofis et al., 2025).

This research focuses on the geochemical and mineralogical characterization of four specific bauxite profiles of different ages in Slovenia, a topic that has remained largely unexplored and represents a significant scientific gap. Despite the small size of Slovenian bauxite occurrence, they offer valuable insight into bauxite formation, deposition, and weathering processes, providing information relevant for regional bauxite horizons comparison and serving as a globally relevant and

interesting case study, as demonstrated by Wang et al. (2010) and Li et al. (2013). Due to the limited thickness of profiles presented in this study, the results should not be directly extrapolated to larger bauxite deposits or considered representative of bauxite systems globally. Nevertheless, their contrasting mineralogical and geochemical characteristics provide an opportunity to examine the processes controlling REE mobilisation, fractionation, and fixation in individual bauxite profiles. The study focuses on the concentration and spatial distribution of trace elements, particularly REE, and on identifying their mineralogical hosts. The main goal of this study is to determine the content and spatial distribution of trace elements, with a focus on REE. By integrating mineralogical characterization and identification of REE carriers, the study aims to clarify the processes controlling element distribution and assess their economic potential. The findings provide site-specific information useful for regional comparison and contribute to broader discussions of REE behaviour in bauxite, but they do not constitute a general genetic model for bauxite, nor do they evaluate the economic aspect of REE extraction.

2. Geological setting

The occurrence of bauxite horizons in Slovenia is relatively common, especially in the Dinaric tectonic unit in the southern part of the country (Fig. 1). However, these occurrences were not of significant economic interest in the past due to their relatively limited size and high silica content. According to their stratigraphic position, eight stratigraphic

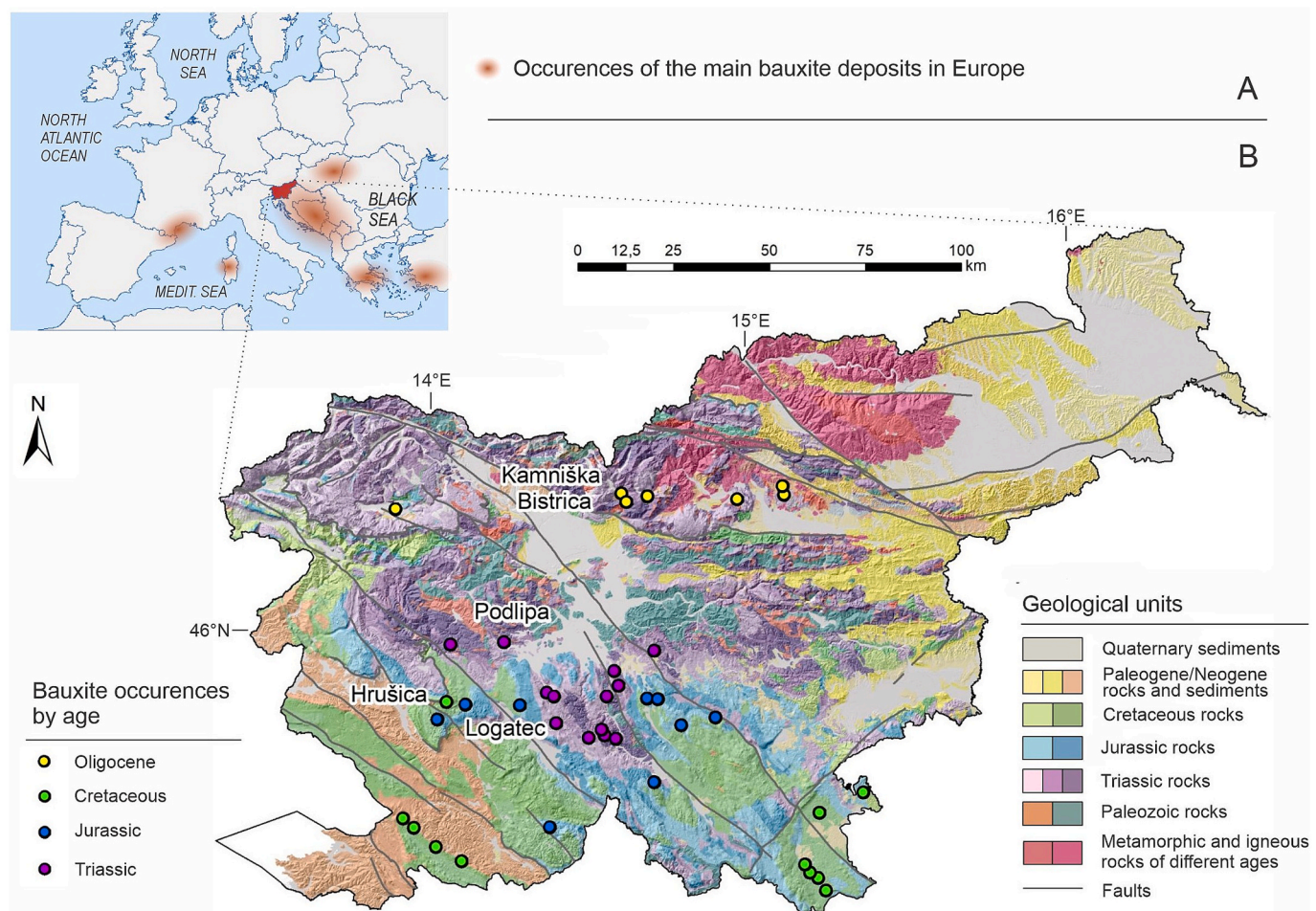


Fig. 1. A – Location map of Europe with marked main occurrences of bauxite deposits in Europe (modified after Meyer, 2004). B – Occurrence of bauxite in Slovenia (Budkovič, 2010) –presented by age and projected on the schematic geological map of Slovenia. Most Oligocene bauxite is present in the northern part while the Craterous bauxite is present mainly in the southeastern and southwestern part of Slovenia. Triassic and Jurassic bauxites mainly occur in the southern part of Slovenia.

horizons with bauxite occurrences have been identified (Buser and Lukacs, 1970):

- (1) Triassic (T_2^{2+3}) – between Anisian and Lower Ladinian sedimentary rocks,
- (2) Triassic (T_3^{2+3}) – between Upper Ladinian and Carnian sedimentary rocks,
- (3) Jurassic ($J_3^{1,2}$) – between Lower Kimmeridgian (Oxfordian) and Upper Kimmeridgian sedimentary rocks,
- (4) Cretaceous (K_{1+2}) – between Lower and Upper Cretaceous sedimentary rocks,
- (5) Cretaceous (K_2^2) – within Turonian rocks,
- (6) Cretaceous ($K_2^{2,3}$) – between Turonian and Santonian,
- (7) Cretaceous ($K_2^{2,3} + P_1$) – between Turonian-Santonian and Palaeocene sedimentary rocks, and
- (8) Oligocene (Ol_2) – between Upper Ladinian and Oligocene.

The map of bauxite occurrences in Slovenia is shown in Fig. 1; the ages of the occurrences are grouped as Triassic, Jurassic, Cretaceous, and Oligocene bauxites.

In the past, these bauxite occurrences were chemically analysed only for the content of the major oxides, while most other elements were not recorded. Bauxite occurrences in Slovenia were subject to sporadic exploration and small-scale mining in the 19th century and the first half

of the 20th century. Systematic exploration of all bauxite occurrences, including drilling programs on the largest and most promising one, took place after the Second World War. By 1970, exploration had ceased, as results indicated that bauxite occurrences are subeconomic as they commonly occur as small, lenticular bodies, commonly with high levels of silica (Štern and Novak, 1962; Lukacs, 1967). Triassic, Jurassic, and Cretaceous bauxites are all deposited on carbonate rocks within the Dinarides, and most commonly occur as lenticular, irregularly shaped layers of reddish-brown colour with an oolitic texture, typically found among limestone formations, except for the Triassic (T_3^{2+3}), which are covered by clastic Carnian beds (Pleničar, 1970; Buser, 1965; Premru, 1983). Oligocene bauxites occur in the Southern Alpine tectonic unit, most commonly in the Kamnik-Savinja Alps; however, their distribution in this region has not yet been thoroughly investigated (Premru, 1983).

In the last few decades, bauxite horizons have been studied mostly for stratigraphic and sedimentary purposes (Toman, 1992); Carnian bauxites have been investigated primarily to establish the sedimentary and stratigraphic relationship between the Ladinian and Carnian beds and to evaluate the sedimentary hiatus between them (Celarc, 2008). Some researchers (Dozet, 1994; Dozet et al., 1993, 1996) focused on the stratigraphy, mineralogy, geochemistry, and genesis of Jurassic bauxites, which display a different geochemical profile (increased contents of aluminium, iron and silica) compared to other bauxite horizons, reflecting a different bauxitic protolith material or a different process of

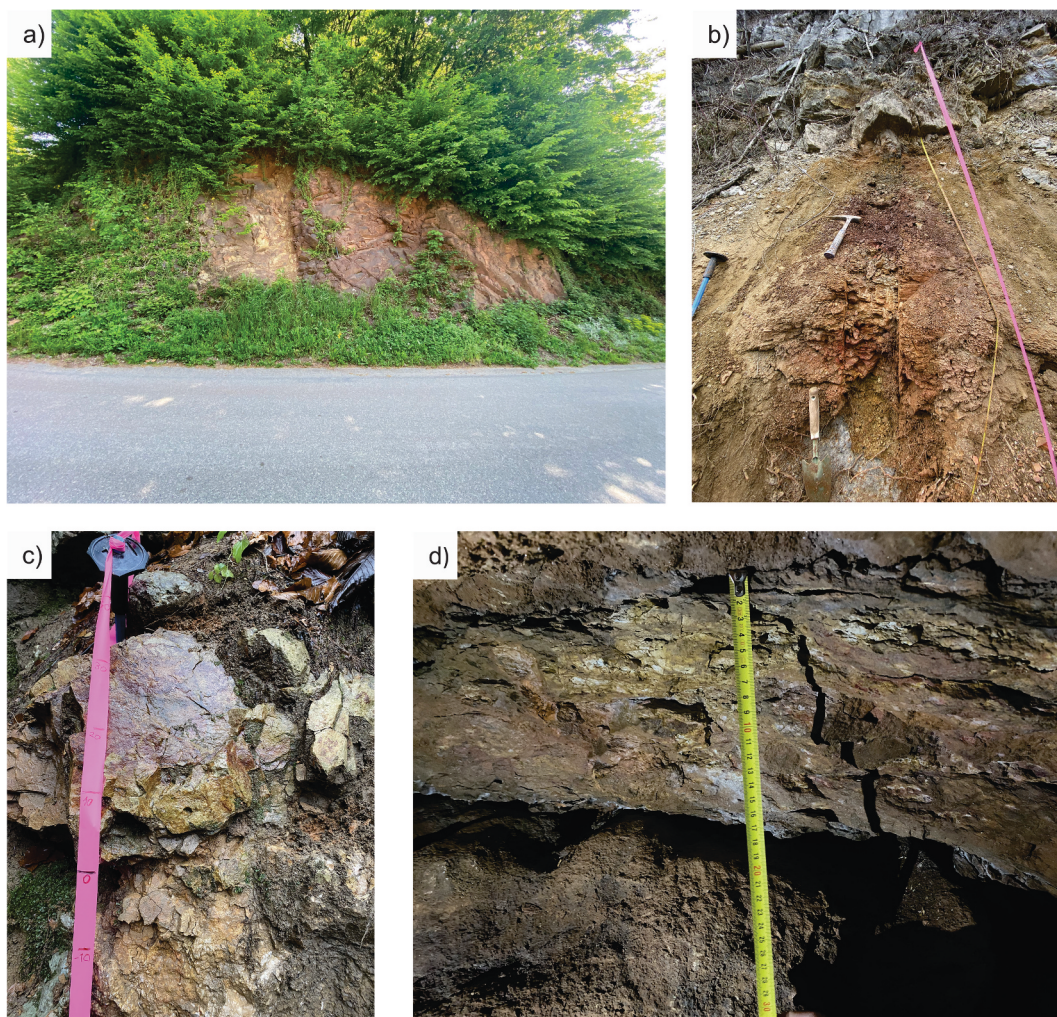


Fig. 2. Triassic bauxite T_2^{2+3} from Podlipa (a), Jurassic bauxite from Logatec $J_3^{1,2}$ (b), Cretaceous bauxite from Hrušica-Nadrt $K_2^{2,3}$ (c) and Oligocene bauxite from Kamniška Bistrica Ol_2 (d). All investigated bauxites, with the exception of Ol_2 bauxite appeared massive with a red to orange colour. The Ol_2 profile is present as layered bauxite occurrence.

genesis.

The most recent analyses of several composite bauxite samples revealed enrichment with REE (Mencinger et al., 2021), which prompted further investigations due to the scientific and socio-economic relevance of the topic.

3. Materials and methods

3.1. Site selection and sampling

To characterise the geochemical variability of bauxite horizons across the stratigraphic profile from footwall to hanging wall, we sought outcrops that expose a continuous and representative section within a single locality. Four bauxite profiles of different ages were selected for analysis, namely:

- Triassic bauxite (T_3^{2+3}) from Podlipa deposited between the Upper Ladinian and Carnian beds (Fig. 2a),
- Jurassic bauxite ($J_3^{1,2}$) from Logatec deposited between the Lower Kimmeridgian (Oxfordian) and Upper Kimmeridgian beds (Fig. 2b),
- Cretaceous bauxite ($K_2^{2,3}$) from Hrušica-Nadrt deposited between the Turonian and Santonian beds (Fig. 2c) and,
- Oligocene bauxite (OL_2) from Kamniška Bistrica deposited between the Upper Ladinian and Oligocene beds (Fig. 2d).

A total of 30 samples were collected. The T_3^{2+3} bauxite lens outcrop in Podlipa, with a thickness of 25 m, was the largest. Ten samples (Pod 01 to 10; Fig. 3a) were collected as point samples at approximately 2.5 m intervals, as the outcrop had a uniform bauxite appearance. The other investigated bauxite profiles were much thinner; therefore, continuous channel samples of 10 cm length were taken through the entire outcrop to represent one sample. Eight samples were collected from the $J_3^{1,2}$ bauxite profile (Lo 01 to 08; Fig. 3b). Sample Lo 01 is a limestone footwall, Lo 02 is weathered bauxite, samples Lo 03 to Lo 05 represent different varieties and consistencies of bauxite, samples Lo 06 and Lo 07 are bauxitic clays that also contain limestone lenses, and sample Lo 08 represents the transition into the silty limestones that overlie the profile. Eight samples were collected from the $K_2^{2,3}$ bauxite (Hr 01 to 08; Fig. 3c).

Sample Hr 01 is a limestone footwall and sample Hr 08 is a bauxitic clay at the contact with the hanging wall. The samples in between represent oolitic bauxite or carbonate breccia with a bauxite matrix. The OL_2 bauxite had the thinnest outcrop, at 35 cm, from which four samples were collected (Kb 01 to 04; Fig. 3d). Samples Kb 01 to Kb 03 represented a 10 cm long channel sample, while the uppermost sample, Kb 04, a bauxitic clay, represented the last 5 cm of the profile.

3.2. Analytical methods

The collected samples were dried for 14 days at 50 °C, ground with a disc mill to a size of 0.05 mm, and homogenised.

General mineral composition was determined by the X-ray powder diffraction method (XRD). Five grams of selected samples (Pod 02, Pod 05, Pod 08, Lo 03, Lo 04, Hr 03, and Kb 03) were analysed with a Phillips PW 3830/40 CuK α diffractometer at a voltage of 40 kV and a current of 30 mA at the Faculty of Natural Science and Engineering, Department of Geology. The source of X-rays was a copper anode. The results were recorded over an angle range of 2° to 70° 2 Theta (θ). The results were further analysed using PANalytical X'Pert Highscore Plus software.

All 30 samples were analysed for geochemical composition. Chemical analyses were done at Activation Laboratories (Actlabs) in Canada using their lithochemistry and whole rock analysis packages 4Litho, 4B1, and 4B-INAA. A minimum of 5 g of sample was mixed with LiBO₂/Li₂B₄O₇ and melted. The cooled samples were digested in nitric acid and analysed by INAA (Au, As, Br, Cr, Cs, Co, Ce, Eu, Hf, Ir, La, Lu, Mo, Nd, Rb, Sb, Se, Sm, Ta, Th, Tb, U, W, and Yb), or by ICP-MS and ICP-OES (SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, K₂O, TiO₂, P₂O₅, MnO, Ag, As, Ba, Be, Bi, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Ga, Gd, Ge, Hf, Ho, In, La, Lu, Mo, Nb, Nd, Ni, Pb, Pr, Rb, Sb, Sc, Sm, Sn, Sr, Ta, Tb, Th, Tl, Tm, U, V, W, Y, Yb, Zn, and Zr). Additionally, ICP-OES analyses following four-acid digestion using hydrochloric, nitric, perchloric, and hydrofluoric acids were used to determine Ag, Cd, Cu, Ni, Pb, S, and Zn.

Analytical precision was assessed by duplicate analyses of five samples, while analytical accuracy was evaluated using reference standard materials Oreas 45d, Oreas 45e, and Oreas 151b. Analytical accuracy for selected samples was good for all elements. Except for Cs and Zn, the relative error was below 10% for Al₂O₃, K₂O, Fe₂O₃, TiO₂, Co,

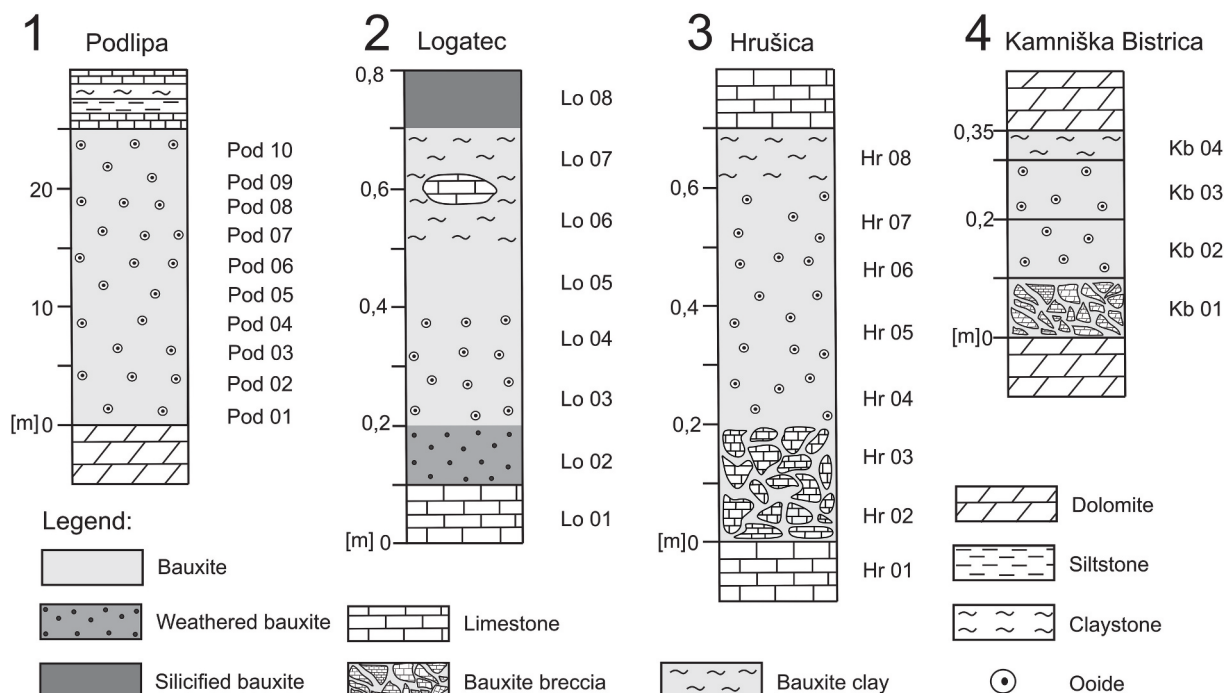


Fig. 3. Stratigraphic columns of investigated T_3^{2+3} , $J_3^{1,2}$, $K_2^{2,3}$ and OL_2 bauxites with marked samples. The profile of Podlipa (T_3^{2+3}) bauxite is not to scale.

and Ni, and less than 1% for V. The precision of the analysis was good for all analysed elements except Ce, Cr, La, Nd, Ta, and Zr. In the analyses performed, Ag, Au, Br, Cs, Ge, and Rb were below the detection limit. In further analysis, we used SiO₂, Al₂O₃, Fe₂O₃, CaO, P₂O₅, TiO₂, Sm, Nd, Zr, and REE. REE contents were normalized to chondritic values (Taylor and McLennan, 1985). Europium anomaly was calculated by McLennan (2012) formula:

$$\text{Eu}/\text{Eu}^* = \text{Eu}_N / \sqrt{(\text{Sm}_N \times \text{Gd}_N)}$$

Cerium anomaly was calculated by Rolloinson (1993) formula:

$$\text{Ce}/\text{Ce}^* = \text{Ce}_N / \sqrt{(\text{La}_N \times \text{Pr}_N)}$$

Polished sections and thin sections were prepared at the Geological Survey of Slovenia from 19 samples by impregnating them with epoxy resin, then cutting with a diamond saw, grinding with carborundum (SiC)–water slurry of grits 600, 800, and 1000, and polishing with 6, 3, and 1 µm diamond suspension fluids.

Polished thin sections of samples Pod 04, Pod 08, Lo 02, Lo 05, Lo 06, Hr 03, Hr 06, and Kb 02 were examined using a Nikon Eclipse E200 optical microscope in polarised light at the Faculty of Natural Science and Engineering, Department of Geology. Images were captured with a Nikon Eclipse E6000 pol microscope equipped with an integrated Nikon DS-Fi1 camera.

Selected polished samples (Pod 03, Pod 04, Pod 06, Pod 08, Pod 09, Lo 01, Lo 02, Lo 03, Lo 05, Lo 06, Lo 07, Hr 03, Hr 05, Hr 04, Kb 01, Kb 02, Kb 03) were examined using scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDS) at the Geological Survey of Slovenia. All samples were carbon-coated and observed in high vacuum in backscattered electron (BSE) mode using a JEOL JSM 6490LV SEM coupled with an Oxford INCA Energy 350 EDS at an accelerating voltage of 20 kV, a working distance of 10 mm, spot size (ss) 48, and an acquisition time of 60 s. Minerals were identified from the atomic proportions of the constituent elements and by comparison with atomic proportions in known stoichiometric minerals from established mineral databases (Anthony et al., 2009; Barthelmy, 2010). The EDS software was calibrated for quantification using premeasured universal standards included in the software, following the fitted standards procedure (Goldstein et al., 2003) referenced to a Co optimisation standard. EDS data were corrected using the standard ZAF-correction procedure included in the INCA Energy software (Oxford Instruments, 2006).

4. Results

4.1. Macroscopic observations of sample locations

The T₃²⁺³ bauxite profile in Podlipa is lenticular, 25 m thick, and in a subvertical position (Fig. 2a). Bauxite was deposited in the karst paleo-relief. The footwall consists of Upper Ladinian dolomite. The bauxite has a brownish-reddish colour and a uniform oolitic texture throughout the profile. Ooids range from 100 to 800 µm in size. The ratio of ooids to matrix is between 30% and 70%. Clear traces of weathering, in the form of iron coatings, are visible throughout the profile. The hanging wall consists of Carnian clastic rocks (siltstone and marlstone) interlayered with thin limestone beds.

The J₃^{1,2} bauxite profile at Logatec, exposed by the highway section, has a lenticular shape and a thickness of 0.8 m (Fig. 2b). It formed at the contact between Lower Kimmeridgian (Oxfordian?) open marine massive oolitic limestone (in the footwall) and Upper Kimmeridgian inner platform (lagoon) well-bedded micritic limestone (in the hanging wall) (Otoničar and Gostinčar, 2016). The bauxite profile has a highly heterogeneous structure and texture, ranging from highly weathered purple-reddish oolitic bauxite to yellowish-orange bauxite that is partially weathered into soft orange clay, especially near the contact with the overlying carbonate rocks, and is partially intercalated with

hard, silicified bauxite of violet colour. A limestone lens is also present within the bauxite horizon, 0.6 m above the footwall. A detailed description of this profile is also available in Dozet et al. (1996).

K₂^{2,3} bauxite, deposited between Turonian and Santonian limestone, is 0.8 m thick and displays a yellowish to brown to reddish colour (Fig. 2c). The bauxite fills the karst paleo-relief in Turonian limestone and has an oolitic texture. At the contact with the hanging wall, a bauxitic clay horizon is present. At the base of the profile, a bauxite breccia occurs, consisting of approximately 55% limestone clasts and 45% bauxitic matrix.

Ol₂ bauxite was deposited on Upper Ladinian massive dolomite and is overlain by Oligocene bedded limestone of the Gornji Grad Formation, indicating a significant hiatus in sedimentation. It has a lenticular shape and is 0.35 m thick (Fig. 2d). The sampled lens is part of a larger infilling of the karst paleo-relief (karst cave) located laterally to the sampling site. At the contact with the footwall, a bauxitic breccia is present. The bauxite breccia consists of approximately 45% limestone clasts and 55% bauxitic matrix. The bauxite profile is layered, has an oolitic texture, and ranges in colour from yellow to orange, occasionally purple. The freshly broken layer is grey and contains pyrite. At the top of the profile, at the contact with the hanging wall, a 5 cm thick bauxitic clay horizon is present. The bauxitic clay is brownish with visible black lamination.

4.2. Petrographic analysis

Bauxites in thin sections are generally brown and only slightly transparent due to the presence of fine-grained minerals containing varying amounts of Fe. In all samples, the texture is mainly oolitic. Ooids are evenly distributed throughout thin sections of T₃²⁺³ bauxite and K₂^{2,3} bauxite, but are unevenly distributed in thin sections of J₃^{1,2} bauxite and Ol₂ bauxite.

In thin sections of T₃²⁺³ bauxite ooids (30%) of different morphologies are embedded within a fine-grained matrix (50%) and contain approximately 5% quartz and about 15% opaque minerals (Fig. 4a). The ooids have concentric internal structures, with some displaying isometric shapes and others showing varying degrees of flattening. Individual ooids are broken (Supplementary Fig. S3; hereafter Fig. S3). In some ooids, zircon inclusions are present, and several are cemented by chalcedony (Fig. 4a). Some quartz grains display epitaxial overgrowths with chalcedony.

J₃^{1,2} bauxite samples are composed of approximately 50% fine-grained matrix, 30% ooids, 15% opaque minerals, and 5% quartz. Quartz appears as discrete grains and as chalcedony. The opaque minerals exhibit a range of morphologies, including spherical, elliptical, rounded, sub-rounded, xenomorphic, and idiomorphic forms. In some cases, smaller quartz grains are enclosed within the opaque mineral grains.

K₂^{2,3} bauxite samples are composed of approximately 60% ooids and 15% fine-grained matrix. Opaque minerals account for about 10% of the total composition, quartz 5%, and iron-bearing minerals an additional 10%. Ooids exhibit concentric structures and commonly contain small grains of opaque minerals and quartz (Fig. 4b). Ooids display a variable number of concentric shells, and some are fractured. Individual ooids exhibit varying degrees of alteration, manifested by differences in the intensity of their brown coloration.

Ol₂ bauxite samples are composed of approximately 70% fine-grained matrix, 15% lithoclasts, 5% muscovite, 5% ooids, and 5% quartz, with rare occurrences of carbonate minerals. Ooids are less abundant than in T₃²⁺³ and K₂^{2,3} bauxite samples. Ooids exhibit a variable number of concentric shells. Individual quartz grains are commonly overgrown by chalcedony cement. Lithoclasts are predominantly composed of fine-grained matrix. Some lithoclasts include individual grains of quartz, opaque minerals, concentric ooids, and bioclasts. Some bioclasts are identifiable as bivalve shells, while others are unrecognisable due to recrystallisation. Some lithoclasts have undergone alteration, resulting in complete replacement by opaque minerals.

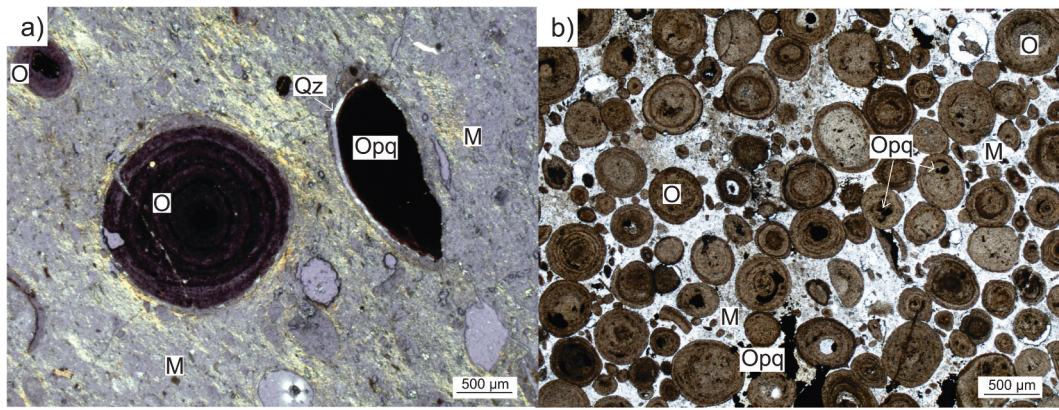


Fig. 4. Ooids (O) in matrix (M) from Triassic bauxite from Podlipa T_3^{2+3} (a) and Cretaceous bauxites from Hrušica K_2^{2+3} (b). Ooids in Triassic bauxite appear in spherical shapes and as broken pieces of ooids. Some are completely altered to the point where no internal structure is noticeable, others are not fully altered. Individual ooids are overgrown with quartz cement (Qz). In Cretaceous bauxites, ooids have concentric shapes with different numbers of shells. Some ooids contain smaller individual grains of opaque minerals (Opq).

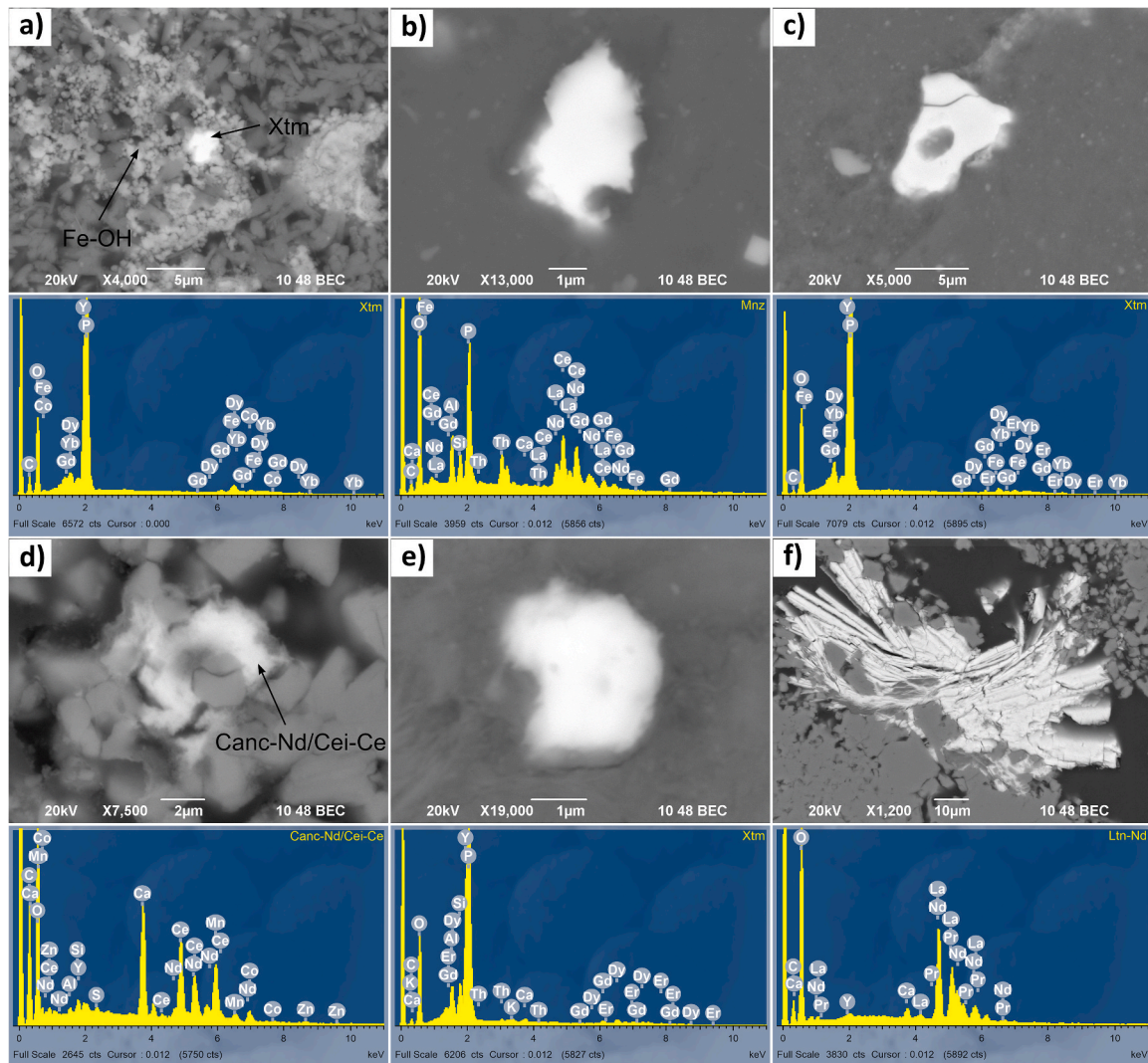


Fig. 5. SEM (BSE) images and EDS spectra of phases in bauxite samples: (a) xenotime (Xtm) in Fe-oxyhydroxide (Fe-OH) (Kb 03); (b) monazite (Ce) (Mnz-Ce) (Hr 03); (c) xenotime (Xtm) on contact between ooids (Hr 03); (d) calcioancylite (Nd) or cerianite (Ce) without Th (Canc-Nd/Cei-Ce) (Lo 01); (e) xenotime (Xtm) (Lo 01); (f) lanthanite-Nd (Ltn-Nd) (Lo 01). The samples are coated with carbon.

4.3. Mineral composition

The mineral composition of the analysed samples, determined by XRD, revealed a generally similar composition for the T_3^{2+3} , $J_3^{1,2}$ and $K_2^{2,3}$ bauxites, with böhmite and kaolinite as the predominant minerals, followed by hematite and small amounts of anatase, possibly ilmenite, and some clinocllore. In the T_3^{2+3} profile, where three samples were analysed, there is a trend of decreasing böhmite and increasing kaolinite content from the bottom to the top of the profile (Fig. S6a, Fig. S6b, Fig. S6c). In the $J_3^{1,2}$ sample, kaolinite predominates over böhmite (Fig. S6d), while in the $K_2^{2,3}$ sample, the opposite is observed (Fig. S6e). The Ol_2 sample differs from the others by the presence of diasporite, which is subordinate to kaolinite and pyrite (Fig. S6f).

According to SEM/EDS analysis, the ooids in the T_3^{2+3} , $J_3^{1,2}$ and $K_2^{2,3}$ bauxites consist of Al-oxide/hydroxide (böhmite), hematite, secondary authigenic Fe-oxyhydroxides (goethite/lepidocrocite), and a kaolinite matrix. In the Ol_2 samples, the oolitic texture is less pronounced, and Al-oxide/hydroxide (diasporite) and kaolinite are present in both the ooids and the matrix (Fig. S1a and S1d). In all samples except T_3^{2+3} , numerous authigenic idiomorphic pyrite grains are present in the matrix, which are already oxidised in the $J_3^{1,2}$ and $K_2^{2,3}$ samples. In addition to pyrite, T_3^{2+3} bauxite contains grains of authigenic chalcophyrite (or

nukundamite), isochalcopyrite, and Ti-hematite. In the Ol_2 samples, pyrite is still preserved to some extent, in both the ooids and the matrix (Fig. S1b). Some individual pyrite grains exhibit oxidation coatings. Inclusions of Ti oxides (anatase), which contain minor Nb in $K_2^{2,3}$, occur in the matrix and ooids of all bauxite samples; ilmenite is present in T_3^{2+3} , $J_3^{1,2}$ and $K_2^{2,3}$, and detrital zircon is found in all samples, with Sc detected in $K_2^{2,3}$. In the T_3^{2+3} sample, some tourmaline grains are observed, and in the $J_3^{1,2}$ samples, secondary authigenic barite is present. In the T_3^{2+3} , $J_3^{1,2}$ and $K_2^{2,3}$ samples, detrital baddeleyite (ZrO_2) grains also occur (Fig. 7c, Fig. 7d). In the $J_3^{1,2}$ samples, pseudobrookite, goyazite, and Mn oxides with minor Ni content are widespread throughout.

Generally, all REE-bearing minerals and phases (shown in Figs. 5–7) are extremely scarce, representing between 0.002 and 0.04% of all minerals and phases in studied samples, and have small mean grain sizes, ranging between 4 and 90 μm . This is why their exact relative abundance is extremely difficult to assess. Monazite (Ce) (Fig. 5b, Fig. 6a, Fig. 6b, Fig. 6f, Fig. 7b, Fig. 7e, Fig. S1c) and xenotime (Fig. 5a, Fig. 5c, Fig. 5e, Fig. 6e) are REE carriers present in all samples and represent 19 and 15%, respectively, of REE-bearing minerals. All monazite (Ce) grains are detrital, have mean grain size ranging between 2 and 13 μm and occur mostly as individual separate grains in bauxitic matrix, but also as inclusions in detrital florencite (La)

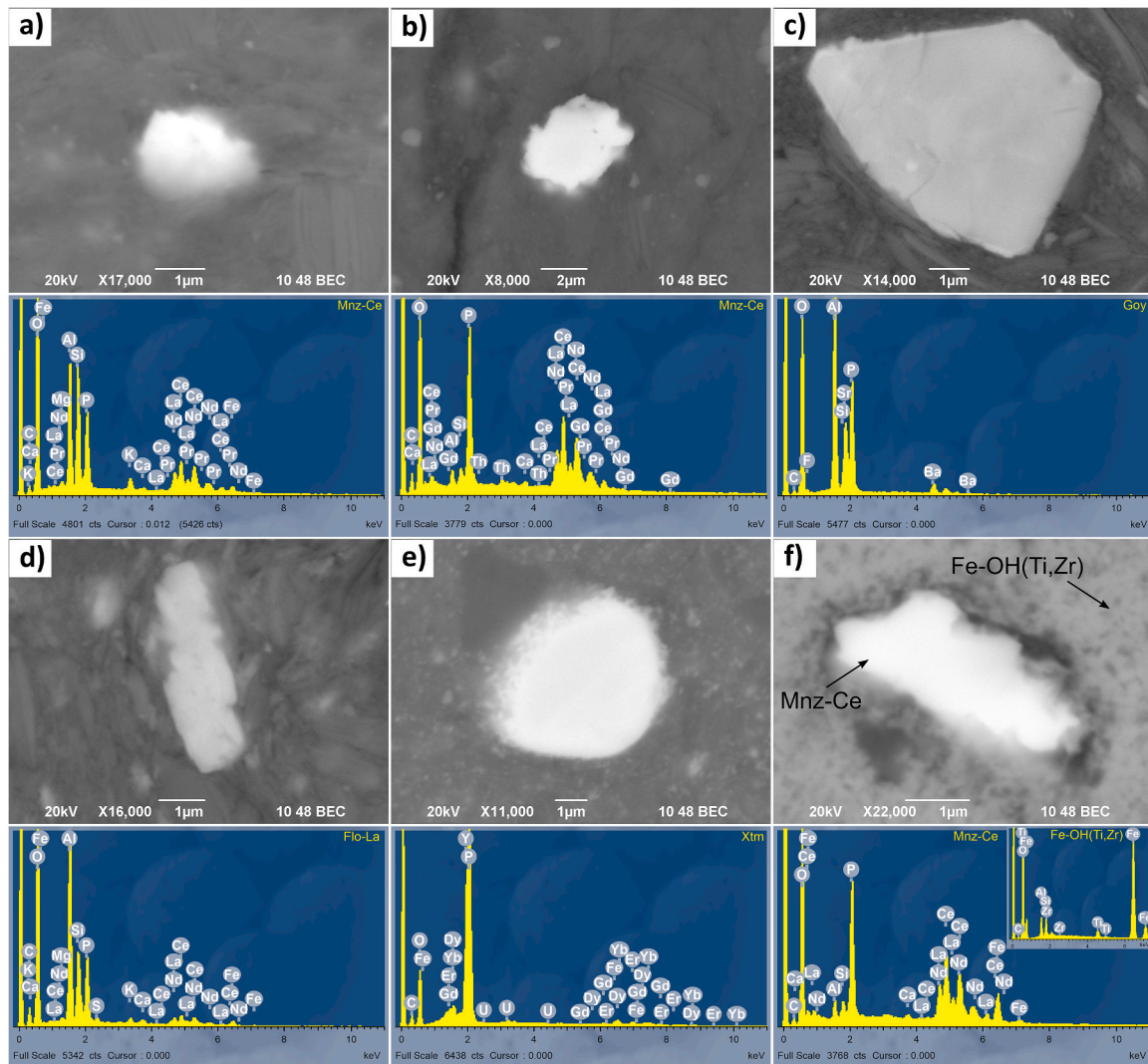


Fig. 6. SEM (BSE) images and EDS spectra of phases in bauxite samples: (a) monazite (Ce) (Mnz-Ce) (Lo 03); (b) monazite (Ce) (Mnz-Ce) (Lo 07); (c) goyazite (Goy) (Lo 07); (d) florencite (La) (Flo-La) (Lo 07); (e) xenotime (Xtm) (Pod 02); (f) monazite (Ce) (Mnz-Ce) in Fe-oxyhydroxide (Ti,Zr) (Fe-OH(Ti,Zr)) (Pod 02). The samples are coated with carbon.

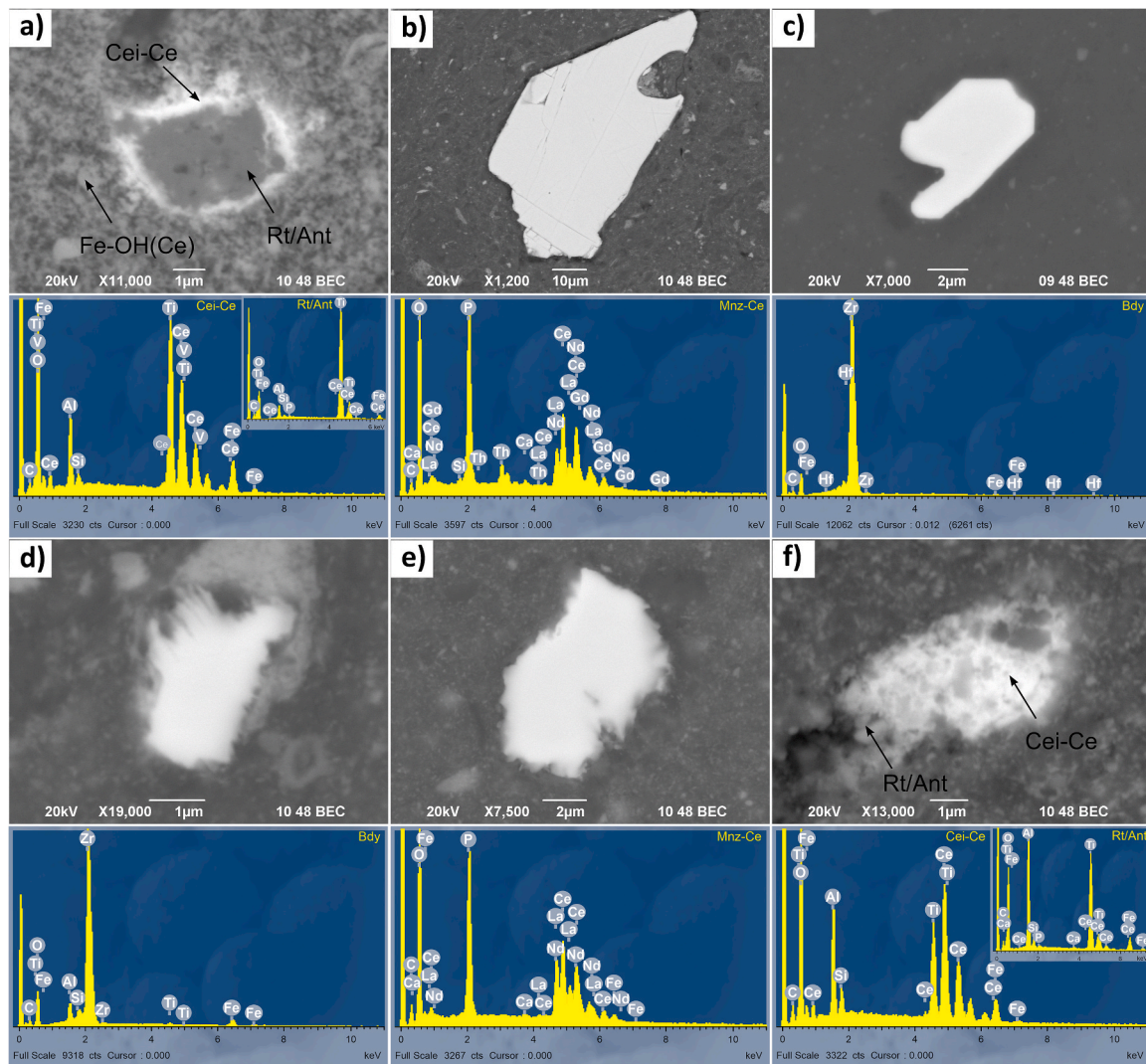


Fig. 7. SEM (BSE) images and EDS spectra of phases in bauxite samples: (a) cerianite (Ce) without Th (Ce-Ce), enveloping rutile/anatase (Rt/Ant) in Fe-oxyhydroxide (Ce) (Fe-OH(Ce)) (Pod 02); (b) monazite (Ce) (Mnz-Ce) (Pod 09); (c) baddeleyite (Bdy) (Hr 03); (d) baddeleyite (Bdy) (Pod 02); (e) monazite (Ce) (Mnz-Ce) (Pod 02); (f) cerianite (Ce) without Th (Ce-Ce) and rutile/anatase (Rt/Ant) (Pod 09). The samples are coated with carbon.

($\text{CeAl}_3(\text{PO}_4)_2(\text{OH})_6$), ilmenite and authigenic Fe-oxyhydroxides with Ti and also Zr. Xenotime is mostly detrital with mean size ranging between 2 and 11 μm and occurs as separate grains within bauxitic matrix, as inclusions within Fe-oxyhydroxide ooids or enveloped with secondary authigenic Fe-oxyhydroxide, except in T_3^{2+3} sample Pod 09 where it is authigenic and in contact with secondary authigenic Fe-oxyhydroxide and also kaolinite. Detrital monazite (Ce) and xenotime often show signs of transport and weathering. Also detrital is quite scarce florencite (La) (Fig. 6d), representing 2% of REE-bearing minerals, which was found only in $\text{J}_3^{1,2}$ sample Lo 07. It occurs mostly as separate grains in bauxitic matrix having mean grain size of 4 μm . A small monazite (Ce) inclusion was found in one of florencite (La) grains.

Secondary authigenic REE-bearing minerals are present in samples from most locations, except $\text{K}_2^{2,3}$ sample Hr 03. The largest and most abundant among secondary authigenic and among REE-bearing minerals in general (representing 45% of REE-bearing minerals) is lanthanite (Nd) and lanthanite (Ce) ($\text{La}_2(\text{CO}_3)_3 \cdot 8\text{H}_2\text{O}$) (Fig. 5f) with mean grain size of 90 μm , which was found only in $\text{J}_3^{1,2}$ sample Lo 01. It occurs as secondary authigenic lamellar to tabular crystals associated with calcite (between calcite crystals) and bauxitic matrix. Cerianite (Ce) (CeO_2) without Th (Fig. 7a, Fig. 7f), together with possible calcioancylite (Nd) ($(\text{Ce,Ca,Sr})\text{CO}_3(\text{OH,H}_2\text{O})$) (Fig. 5d, Fig. S1f), are third most

abundant, reaching 6 and 7%, respectively, of REE-bearing minerals. They mostly form aggregates of minute crystallites with mean sizes between 3 and 23 μm and are associated with other minerals. They occur within bauxite clasts, within large ooids composed of secondary authigenic Fe-oxyhydroxide and Al-oxide/hydroxide (böhmite), enveloping rutile/anatase, as inclusions in Ti-bearing hematite, as thin crusts (impregnations) at the contacts between bauxitic matrix and calcite, between calcite grains filling spaces between calcite crystals, in contact with Mn oxides with Ni and Co and in contact with Fe-oxyhydroxides with V. Possible calcioancylite (Nd) was found only in $\text{J}_3^{1,2}$ sample Lo 01. Other scarce REE-bearing phases (representing 1 and 4% of REE-bearing minerals) present only in $\text{J}_3^{1,2}$ sample Lo 01, are secondary authigenic Fe-oxyhydroxides and Mn oxides with minor Ni and Co, which both contain minor Ce and have mean grain sizes of 4 and 27 μm , respectively. They are composed of minute crystallites and occur at the contact between calcite and bauxitic matrix.

Particularly detrital REE-bearing minerals monazite (Ce), xenotime and florencite (La) are well dispersed within the samples, while secondary authigenic REE-bearing minerals are relatively concentrated in certain areas of the samples.

4.4. Geochemistry

The carbonate bedrock hosting the bauxite deposits consists of high-purity limestones. In south-western Slovenia, limestones typically contain only 1–2% insoluble residue (Gams, 1974, 2003; Ogorelec and Rothe, 1993), while Cretaceous–Palaeocene limestones contain approximately 1% insoluble residue (Zupančič et al., 2018). Based on these observations, Zupančič et al. (2018) concluded that even in rendzinas, limestone weathering is not the principal source of soil material. Similarly, Triassic limestones in neighbouring Austria (Küfmann, 2003) and Mesozoic carbonates in Croatia (Herak, 1972) are characterised by very low insoluble residue. Consequently, limestone weathering is unlikely to have been a significant source of material for bauxite formation (Bárdossy and Boni, 1977). Instead, the karstified limestone surface primarily functioned as a trap for aeolian and water-transported sediments (Bárdossy and Boni, 1977; Pajović, 2009), which accumulated as a thin cover over the carbonate platform and subsequently underwent lateritisation and local remobilisation (Boni et al., 2013).

Whole rock major oxide and REE contents for all analysed bauxite samples are presented in Table 1 and Table 2. Whole rock trace element contents are provided in Supplementary Table S1.

Al₂O₃ content generally dominates in all samples, ranging from 8.5% (Lo 01 – limestone) to 67% (Hr 07), with a median of 37.3%. This is followed by SiO₂, which ranges from 5% (Hr 06) to 61% (Pod 01), with a median of 30.6%. Exceptions include the most silicified upper and lower parts of the T₃²⁺³ profile, where SiO₂ content slightly exceeds Al₂O₃ content, and the J₃² profile, where the contents of both oxides are nearly equal. Fe₂O₃ content is variable, with a minimum of 2.3% (Hr 02), a maximum of 19.8% (Pod 03), and a median of 9.3%. TiO₂ content ranges from 0.7% (Pod 01) to 2.85% (Hr 04–07), with a median of 1.5%. The contents of other major oxides are generally very low, except for the high CaO contents (40%) in the lowest J₃² (Lo 01 – limestone) and K₂³ (Hr 02 – breccia with limestone clasts) samples.

The REE content in the analysed bauxites is presented in Table 3 and Table S2. The sumREE content, calculated as the sum of La to Lu, ranges from 107 mg/kg (Hr 02) to 1710 mg/kg (Lo 01), with a median of 615

Table 2

Trace element content of investigated bauxites in mg/kg.

Sample	Cr	Ga	Ni	Zr
Pod 01	40	23	50	178
Pod 02	48	38	90	491
Pod 03	161	58	125	723
Pod 04	94	39	130	605
Pod 05	94	47	120	602
Pod 06	107	48	120	628
Pod 07	91	41	140	552
Pod 08	121	47	110	650
Pod 09	65	28	110	431
Pod 10	35	33	50	482
Lo 01	90	9	90	51
Lo 02	262	35	110	212
Lo 03	256	42	160	291
Lo 04	238	39	150	322
Lo 05	226	38	140	315
Lo 06	236	39	150	322
Hr 01	18	1	30	12
Hr 02	132	12	110	132
Hr 03	328	43	400	394
Hr 04	439	56	330	577
Hr 05	502	62	330	586
Hr 06	431	57	320	570
Hr 07	440	59	320	569
Hr 08	193	26	420	239
Lo 07	167	28	90	233
Lo 08	184	31	110	271
Kb 01	136	28	190	394
Kb 02	130	31	130	414
Kb 03	131	34	90	424
Kb 04	139	29	180	411

mg/kg. In the T₃²⁺³ profile, sumREE content ranges from 350 to 820 mg/kg, with most values between approximately 600 and 700 mg/kg. In the J₃² profile, sumREE content is mainly between 420 and 700 mg/kg, with an extreme value of 1710 mg/kg at the bottom of the profile. In the K₂³ profile, sumREE content is generally three times lower than in the other profiles, with values between 110 and 300 mg/kg. In the Ol₂

Table 1

Chemical composition of investigated bauxites – major oxides in %.

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	LOI
Pod 01	60.91	17.51	7.05	1.96	0.22	0.17	4.70	0.66	0.05	0.33	6.99
Pod 02	42.52	33.69	7.46	0.38	0.32	0.93	1.85	0.75	0.07	0.06	12.08
Pod 03	8.06	57.82	19.80	0.11	0.05	0.03	0.11	1.95	0.06	0.05	12.55
Pod 04	30.92	46.83	3.93	0.21	0.12	0.06	0.21	1.42	0.06	0.03	15.27
Pod 05	22.67	47.80	14.03	0.20	0.09	0.04	0.14	1.50	0.04	0.05	13.83
Pod 06	22.36	49.84	12.35	0.16	0.07	0.04	0.15	1.53	0.05	0.03	13.89
Pod 07	27.90	42.97	13.11	0.15	0.08	0.04	0.16	1.40	0.07	0.05	13.44
Pod 08	21.70	49.47	12.41	0.15	0.10	0.05	0.17	1.62	0.04	0.04	14.75
Pod 09	39.20	33.84	11.57	0.11	0.16	0.05	0.15	1.10	0.06	0.03	14.24
Pod 10	47.2	27.8	9.33	0.13	0.28	0.06	0.37	1.03	0.02	0.02	12.20
Lo 01	8.77	8.53	3.83	0.50	41.19	0.07	0.57	0.22	0.03	0.07	35.90
Lo 02	31.96	31.62	16.48	1.30	0.26	0.21	2.25	1.07	0.05	0.02	13.62
Lo 03	33.80	39.57	7.12	1.40	0.34	0.21	2.38	1.53	0.04	0.03	13.77
Lo 04	32.46	35.75	13.81	1.29	0.36	0.19	2.37	1.67	0.04	0.06	11.80
Lo 05	33.33	35.50	13.67	1.28	0.33	0.20	2.55	1.65	0.03	0.07	11.81
Lo 06	34.24	34.07	6.43	1.33	3.79	0.21	2.60	1.64	0.04	0.04	14.58
Lo 07	26.00	25.71	4.53	1.20	17.12	0.18	2.05	1.20	0.04	0.06	20.53
Lo 08	31.65	27.69	7.78	1.22	6.85	0.24	2.64	1.39	0.04	0.02	18.80
Hr 01	1.63	1.41	0.70	0.20	54.59	0.01	0.01	0.05	0.01	0.01	42.01
Hr 02	6.46	16.33	2.32	0.19	39.85	0.02	0.02	0.69	0.01	0.01	34.53
Hr 03	12.05	47.59	7.18	0.25	10.63	0.03	0.13	2.00	0.06	0.03	20.62
Hr 04	8.15	65.72	7.18	0.14	0.14	0.02	0.03	2.78	0.05	0.02	15.32
Hr 05	6.05	66.11	7.57	0.11	0.08	0.03	0.02	2.82	0.06	0.02	15.65
Hr 06	5.01	65.89	8.99	0.09	0.04	0.02	0.02	2.77	0.05	0.02	15.87
Hr 07	5.96	66.85	8.54	0.11	0.08	0.02	0.02	2.77	0.05	0.02	15.33
Hr 08	18.90	28.22	11.42	0.18	16.84	0.03	0.11	1.18	0.14	0.03	23.32
Kb 01	31.00	35.25	13.52	0.20	1.21	0.05	0.35	1.62	0.21	0.09	15.62
Kb 02	30.56	37.34	11.11	0.18	0.12	0.05	0.45	1.72	0.19	0.10	18.12
Kb 03	31.96	37.96	9.49	0.18	0.06	0.05	0.49	1.74	0.20	0.06	17.37
Kb 04	31.73	37.58	12.58	0.21	0.20	0.04	0.44	1.67	0.19	0.09	15.33

Table 3

Content of sumREE, LREE and HREE in investigated bauxites in mg/kg.

		T_3^{2+3}	$J_3^{1,2}$	$K_2^{2,3}$	Ol_2
sumREE	Mean	641	711	218	646
sumREE	Min	351	421	107	615
sumREE	Max	822	1710	289	689
sumREE	St. Dev.	147	387	52	28
LREE	Mean	574	658	199	605
LREE	Min	317	386	100	572
LREE	Max	741	1614	264	646
LREE	St. Dev.	118	370	47	28
HREE	Mean	67	53	19	41
HREE	Min	34	35	8	39
HREE	Max	82	97	24	43
HREE	St. Dev.	19	18	5	2

samples, the range of sumREE is the narrowest, between 615 and 690 mg/kg. In all four profiles, on average, LREE contents are ten times higher than HREE contents.

The vertical distribution of LREE and HREE in the analysed profiles is very similar, with LREE content being much higher (Fig. 8). The trend between LREE and HREE content differs only at three sampling points: Lo 03, Hr 07, and Kb 04. Therefore, we focus on the distribution of sumREE from this point onwards. In the T_3^{2+3} and $K_2^{2,3}$ profiles, the middle of the profile is most enriched with sumREE, with exception of Pod 04 sample. In the $J_3^{1,2}$ profile, an extremely high content is observed in the lowest sample, Lo 01. In all other samples, the contents are significantly lower, with a slightly increased content in Lo 03. In the Ol_2

profile, the differences are not very large.

Chondrite-normalised REE patterns (Table S3; normalised to chondrite values after Taylor and McLennan, 1985) are broadly similar across all bauxite samples, displaying nearly parallel distributions characterised by pronounced LREE enrichment, relatively flat HREE patterns, a consistent negative Eu anomaly, and variable Ce anomalies. Samples that deviate slightly from this general trend: the lowermost sample of the $J_3^{1,2}$ profile (Lo 01), representing the underlying limestone, which exhibits substantially higher total REE contents, and the Hr 02 limestone–bauxite breccia sample, which is characterised by comparatively lower REE contents.

The average LREE/HREE ratio (Table S2) is highest in the Ol_2 profile (14.7), followed by the $J_3^{1,2}$ (12.0), $K_2^{2,3}$ (10.6), and T_3^{2+3} (8.7) profiles. In contrast, REE fractionation, expressed by chondrite-normalised (La/Yb)_N ratios (Table S3), is greatest in the $J_3^{1,2}$ profile (18.7), followed by the Ol_2 (12.7), $K_2^{2,3}$ (7.3), and T_3^{2+3} (6.9) profiles. This fractionation is primarily controlled by the LREE, as reflected by the (La/Sm)_N ratio (Table S3), which averages approximately 3 in the Ol_2 , $K_2^{2,3}$, and T_3^{2+3} profiles but reaches an average value of 6 in the $J_3^{1,2}$ profile. Conversely, HREE fractionation is relatively limited, with (Gd/Yb)_N values ranging from 1.8 in the Ol_2 profile to 1.1 in the $K_2^{2,3}$ profile.

T_3^{2+3} samples have a slightly negative or positive Ce anomaly, $K_2^{2,3}$ samples have a very slightly negative Ce anomaly, and $J_3^{1,2}$ and Ol_2 samples show a clear negative Ce anomaly. All samples have a negative Eu anomaly (Fig. 9; Table S2).

The Kruskal-Wallis analysis of variance confirmed differences between all four bauxites of different ages in the content of all major

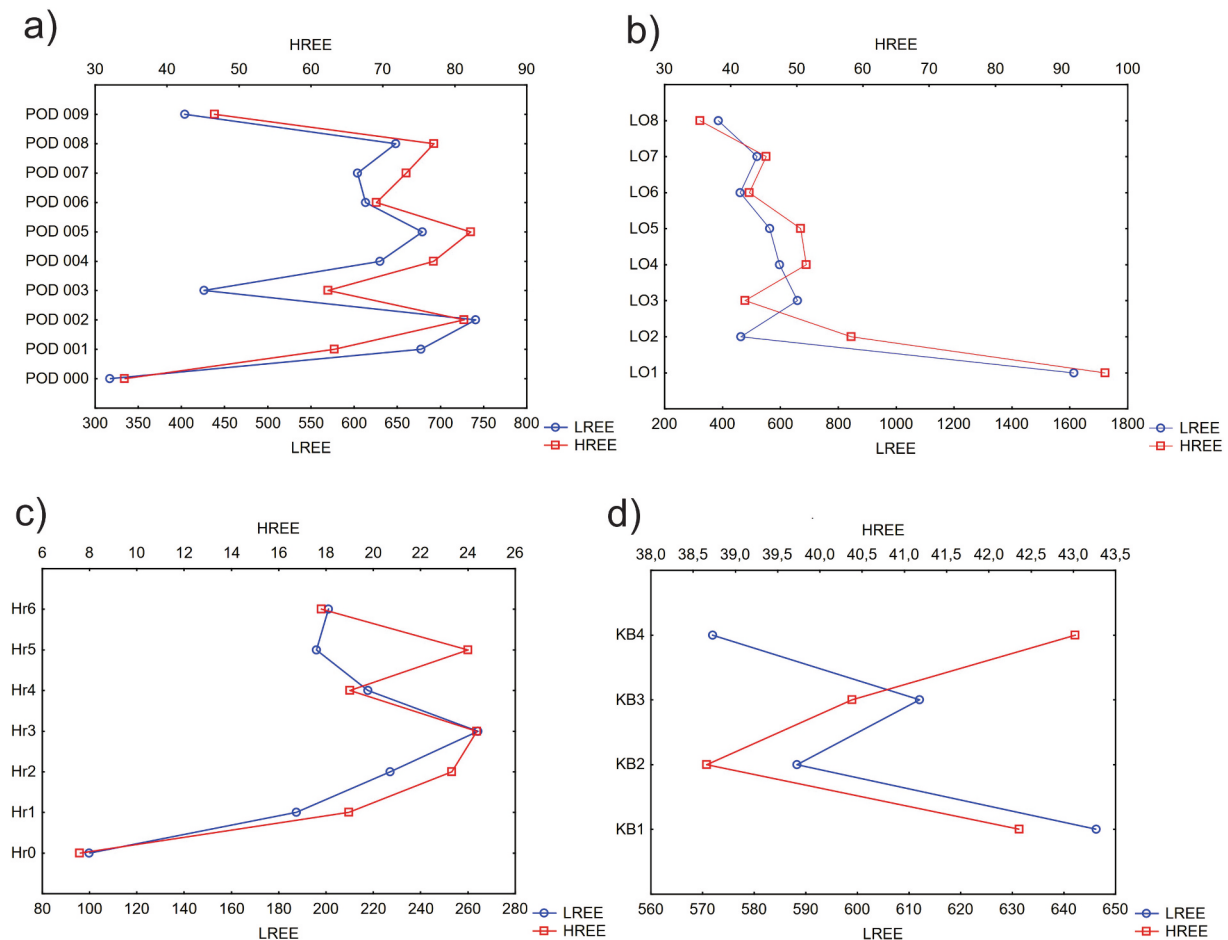


Fig. 8. Distribution of LREE (blue) and HREE (red) in investigated bauxites – a) Podlipa T_3^{2+3} , b) Logatec $J_3^{1,2}$, c), Hrušica $K_2^{2,3}$ and d) Kamniška Bistrica Ol_2 . The diagrams highlight systematic vertical geochemical trends and differences between the sections, including strong enrichment in the lower part of some profiles and variable LREE/HREE behaviour among the sites.

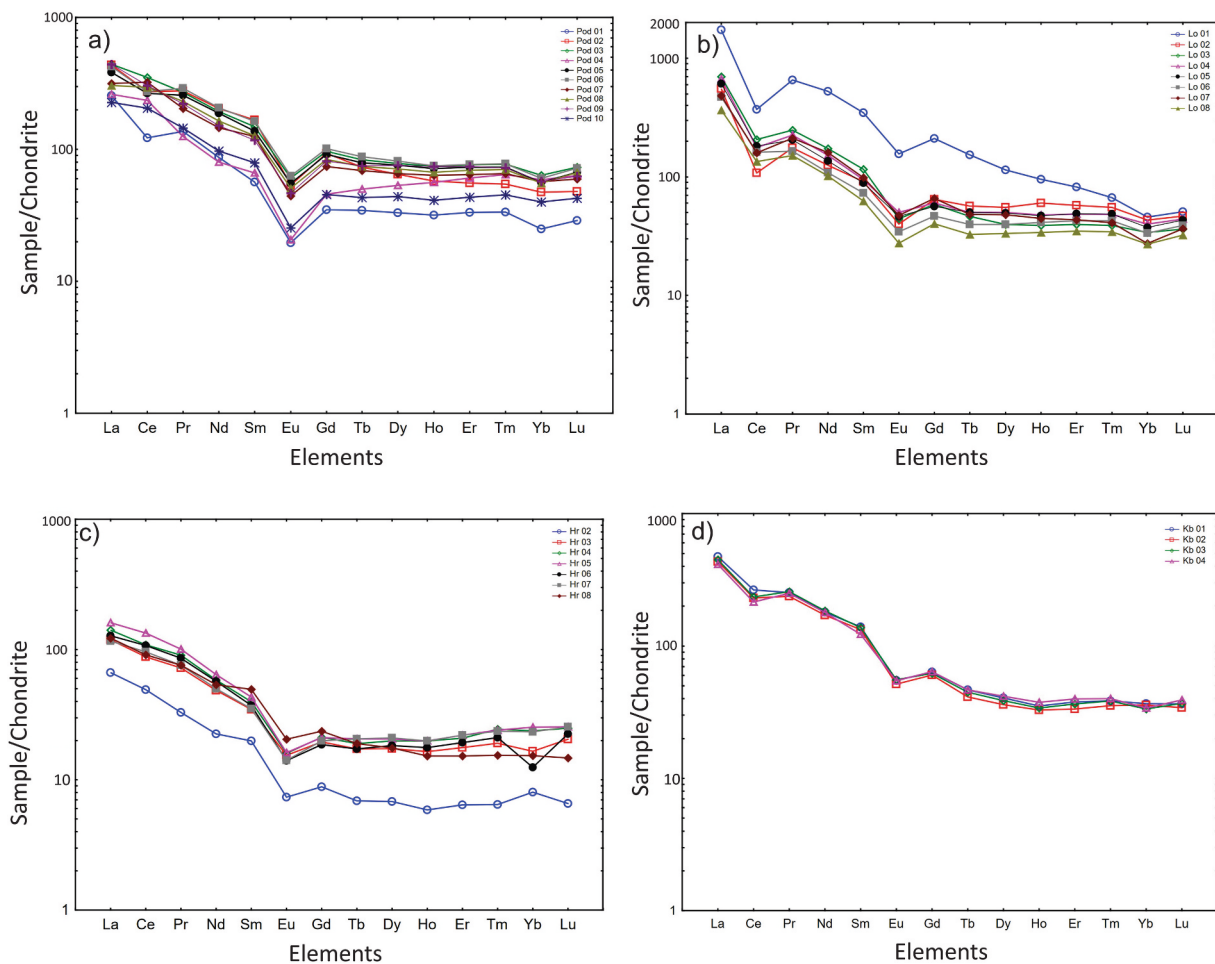


Fig. 9. Chondrite normalized REE patterns of investigated bauxites (Taylor and McLennan, 1985) – a) Podlipa T_3^{2+3} , b) Logatec $J_3^{1,2}$, c), Hrušica K_2^{2+3} and d) Kamniška Bistrica Ol_2 . Panels a–d show the individual profiles, with most samples displaying strong light REE enrichment, pronounced depletion in Eu, and relatively flat heavy REE segments. The patterns indicate broadly similar REE fractionation trends among the studied profiles, with local variations in overall REE abundance and the degree of LREE enrichment.

oxides, except Al_2O_3 , Fe_2O_3 , Ga, and Sc. These statistical differences primarily arise from the deviation of a single profile compared to the others. The $J_3^{1,2}$ profile has high K_2O , MgO , and Na_2O contents; in the K_2^{2+3} profile, SiO_2 and sumREE contents are significantly lower and Al_2O_3 and TiO_2 contents are higher; and the Ol_2 profile has high MnO and P_2O_5 contents. The T_3^{2+3} site is characterised by high variability in the content of all elements except CaO and P_2O_5 , $J_3^{1,2}$ by CaO and sumREE, K_2^{2+3} by high variability of TiO_2 , CaO and P_2O_5 , and Ol_2 by SiO_2 , Fe_2O_3 and P_2O_5 contents.

In the T_3^{2+3} profile (Fig. 10a), SiO_2 contents are very high in the lower (Pod 01) and upper (Pod 10) samples, decreasing towards the centre of the profile, where they show slight variation. In the $J_3^{1,2}$ profile (Fig. 10b), SiO_2 content is low at the deepest sampling point and increases irregularly up the profile. In the K_2^{2+3} profile (Fig. 10c), SiO_2 content is very low except in the uppermost sample. In the Ol_2 profile (Fig. 10d), SiO_2 content changes slightly above 30%. The Al_2O_3 distribution patterns are generally the opposite of SiO_2 in all profiles except $J_3^{1,2}$, where both elements display similar distributions. In all profiles, Al_2O_3 , TiO_2 , and Zr (Fig. 10) contents are generally lowest at the bottom and top of the profile and highest in the middle. However, in the T_3^{2+3} profile, contents in the centre vary in a zigzag pattern.

In the analysed profiles, Fe_2O_3 distribution shows different patterns (Fig. 10). With some exceptions, Fe_2O_3 contents are lowest at the boundaries with footwall of the T_3^{2+3} and $J_3^{1,2}$ profiles, and highest in the Ol_2 profile. In the K_2^{2+3} profile, there is a continuous increase from the bottom upwards. Only in the T_3^{2+3} profile does the Fe_2O_3 distribution

roughly match those of Al_2O_3 and TiO_2 . CaO contents are generally highest at the top and bottom of the profiles, which is the opposite of the Al_2O_3 and TiO_2 distributions. The P_2O_5 distribution throughout the profiles appears to be random (Fig. 10).

Comparison of sumREE distribution in the profile with the distribution of other elements that are major constituents of the minerals with which REEs could be associated shows that there are generally no simple relationships indicating only one type of carrier in the same profile or even in the same sample. For each profile, elements showing REE content trends that coincide with those of other elements within the same samples were identified. Al hydroxides and oxyhydroxides with complex geochemical paragenesis appear to be important in Pod 03, Pod 06, Hr 05, Kb 01 and Kb 03. Fe-bearing minerals (Fe-oxyhydroxides (goethite/lepidocrocite), hematite, ilmenite) could play a role in Pod 03 and Kb 01, carbonates in Lo 01, Lo 07 and Kb 01, and phosphates in Pod 09, Hr 05 and Kb 03.

5. Discussion

5.1. Major minerals

Aluminium in bauxites initially precipitates as gibbsite [$Al(OH)_3$] or amorphous aluminium hydroxides (Putzolu et al., 2018). However, in our T_3^{2+3} to K_2^{2+3} profiles, böhmite and, in the Ol_2 profile, diasporé are the main aluminium carriers. Böhmite [$\gamma-AlO(OH)$] and diasporé [$\alpha-AlO(OH)$] form through dehydration during diagenetic changes at

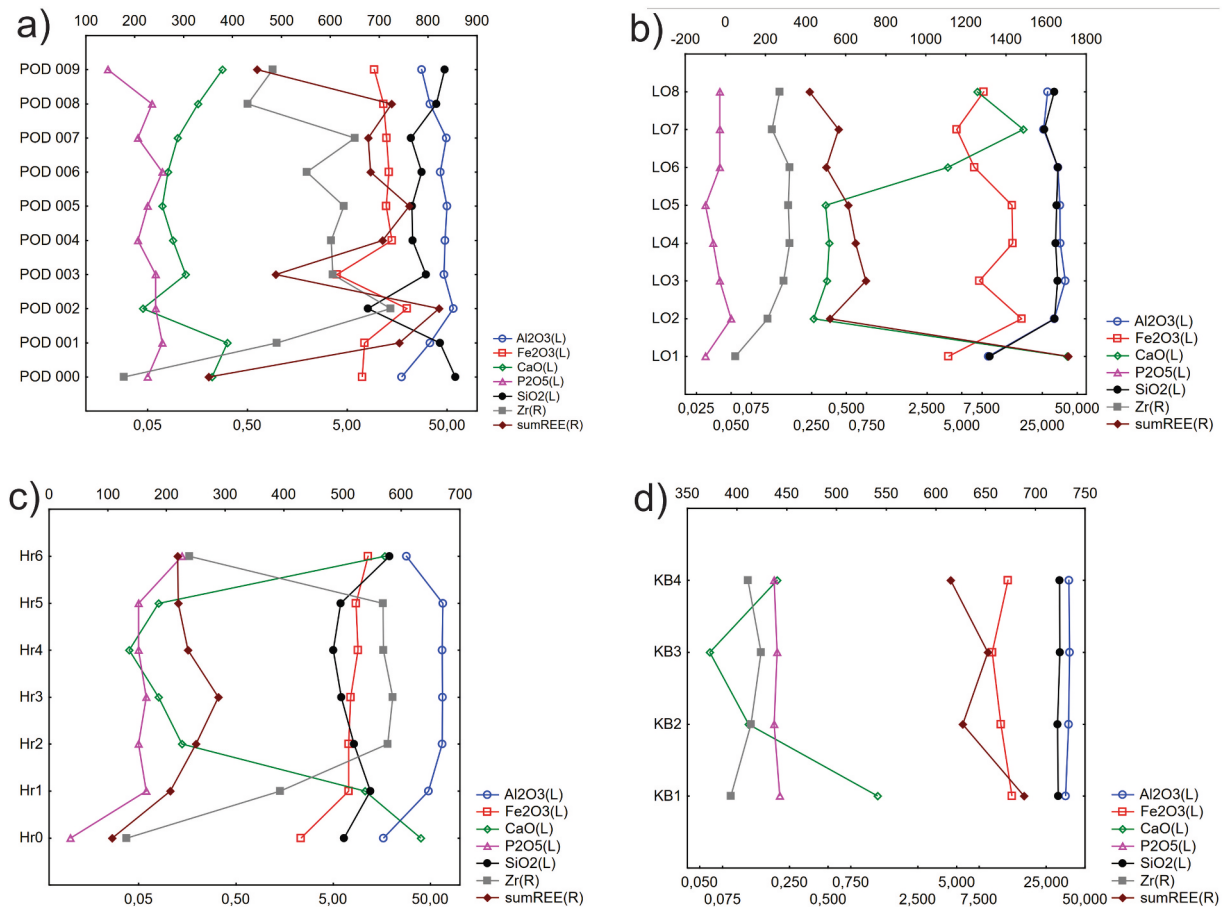


Fig. 10. Distribution of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , TiO_2 , P_2O_5 sumREE and Zr in investigated bauxites. The geochemical profiles demonstrate progressive chemical weathering characterized by depletion of mobile constituents (CaO and P_2O_5) and relative enrichment of immobile components (Al_2O_3 and Fe_2O_3). Variations in the Zr and ΣREE indicate that resistant minerals and REE were unevenly redistributed during weathering, with the strongest REE enrichment occurring in the T_3^{2+3} and $\text{J}_3^{1,2}$ profiles and comparatively weaker enrichment in the $\text{K}_2^{2,3}$ and O_2 profiles. These patterns suggest differences in weathering intensity, drainage conditions, and element mobility among the four lateritic profiles.

temperatures of 35–50 °C (Valeton, 1972; Temur et al., 2006) and/or metamorphism (Boni et al., 2013). Bauxites that have undergone several diagenetic stages are therefore mainly composed of böhmite, as is the case for the studied T_3^{2+3} , $\text{J}_3^{1,2}$ and $\text{K}_2^{2,3}$ profiles, which is less hydrated than gibbsite, and diasporite (Fig. S1d; Boni et al., 2013), which is typical for O_2 samples.

At least in some parts of the analysed profiles, all bauxites show an ooid texture, with ooids displaying alternating more and less iron-rich shells within the kaolinite matrix, indicating good drainage conditions throughout the profiles. Good drainage within the profile remobilises aluminium and iron oxyhydroxides, which precipitate on the surface of ooids, causing them to grow concentric shells. XRD and EDS analyses show the presence of hematite, also with minor content of Ti, and secondary authigenic iron oxyhydroxides (goethite/lepidocrocite), which in places also contain minor amounts of Al, Si, Mn, Ti, Zr and Ce. SEM/EDS analysis of the ooids shows that they are composed of alternating layers of purer böhmite and layers of a mixture of böhmite and microcrystalline iron oxyhydroxides (goethite/lepidocrocite) (Fig. S2c).

Another possibility is the formation of böhmite in bauxite-bearing ooids during the pedogenetic process at low water activity, as described by Mongelli et al. (2016) and references therein.

Finally, böhmite and hematite in bauxite may form by the dehydration of gibbsite and goethite, respectively, in tropical climates with a pronounced dry season and relatively high temperatures (Salamab-Ellahi et al., 2019). During bauxitisation, iron separates from aluminium and concentrates mainly in hematite and to a lesser extent, in goethite (Boni et al., 2013), in our case in goethite/lepidocrocite.

Due to the presence of small detrital grains of unaltered goethite/lepidocrocite in the matrix and ooids, we propose that the formation of hematite and goethite/lepidocrocite was driven by the dehydration of gibbsite and goethite to form hematite. This was followed by hydration, producing small grains of goethite/lepidocrocite in the matrix and ooids, while larger hematite grains were slightly altered. According to Mongelli (2002), iron-bearing concretions form in a water-unsaturated, dry environment that favours the stability of böhmite rather than Al-hematite, alternating with a more humid climate that favours the stability of Al-hematite. SEM/EDS analysis of the investigated bauxites revealed the presence of hematite, with occasional occurrence of Ti, instead of Al-hematite.

Tardy (1997) suggested that kaolinite and hematite coexist in an almost “amorphous” phase and that böhmite forms by desilification and dehydration, together with rings or cores of hematite. Another possibility is the formation of böhmite in the concretions due to local reducing conditions that promote the instability of hematite (Biber et al., 1994).

In all samples except T_3^{2+3} , we found evidence of reducing conditions indicated by the presence of authigenic pyrite in the matrix. In the case of the $\text{J}_3^{1,2}$ and $\text{K}_2^{2,3}$ samples, which are already limonitised, indicate the transition to an oxidising environment. In all inspected clay samples, kaolinite is the prevailing or even the only identified clay mineral (Fig. S2a). Kaolinite is a weathering product of aluminosilicates (Tomašić et al., 2021), which could be the case in the $\text{J}_3^{1,2}$ and O_2 samples, where kaolinite prevails over Al-hydroxides. Another possibility is its epigenetic formation due to the circulation of SiO_2 -rich

solutions through microcracks. Such low pH solutions could lead to the silicification of böhmite present in the matrix (Mameli et al., 2007), as has been observed in some karst bauxite deposits in the Mediterranean (Bárdossy, 1982; Dangić, 1985, 1988). The addition of SiO_2 in T_3^{2+3} , $\text{J}_3^{1,2}$ and O_2 bauxites is supported by observed chalcedony and quartz-filled veins (Fig. 4a). The SiO_2 contents in T_3^{2+3} samples are highest at the boundaries of the profile, indicating that discordant contacts of bauxite with the hanging wall could be the pathway for SiO_2 -rich solutions (Fig. 10a).

As suggested by Karadağ et al. (2009), dehydration combined with diagenetic processes could also transform gibbsite and böhmite into kaolinite. The coexistence of these minerals depends not only on the activity of silica but also on that of water. A decrease in water activity leads to dehydration, as does an increase in temperature (Tardy et al., 1990). Dehydrated minerals are observed in all studied bauxites, which may be related either to diagenetic dehydration or to tropical climatic conditions with prolonged dry periods (Trolard and Tardy, 1987).

In O_2 bauxite, the main Al-bearing mineral is kaolinite, with subordinate diaspore (Fig. S1d). The coexistence of kaolinite and diaspore indicates that diaspore was probably formed in the initial stages by the destruction of kaolinite (Dangić, 1988; Meshram and Randive, 2011). The presence of diaspore and pyrite is typical of mildly reducing conditions (D'Argenio and Mindszenty, 1995).

Anatase and ilmenite are the main carriers of TiO_2 in all four profiles (Fig. 7f, Fig. S2d). In all profiles, both occur as anhedral grains, indicating a possible detrital source. In the case of T_3^{2+3} samples, ilmenite also appears to be authigenic (Pod 07). In $\text{J}_3^{1,2}$, $\text{K}_2^{2,3}$ and O_2 bauxites, anhedral anatase grains (Hr 03) probably formed syngenetically with the bauxites (Tomašić et al., 2021). Authigenic anatase indicates more reducing conditions during the formation of the karst bauxite (Ahmadnejad et al., 2017). This is also supported by the presence of authigenic pyrite in O_2 bauxite (Fig. S1b). According to D'Argenio and Mindszenty (1995) O_2 bauxites correspond to phreatic bauxites, due to their mineral composition, observed organic residues, and the random distribution of trace elements in the profile. In $\text{J}_3^{1,2}$ and $\text{K}_2^{2,3}$ bauxites, pyrite has already altered to hematite and goethite/lepidocrocite, which supports a change to an oxidising environment. Such a mineral assemblage indicates a change in Eh conditions during bauxitisation and/or diagenesis, i.e. a change in the water table in karstic depressions filled with bauxitic material (Tomašić et al., 2021). The oxidised authigenic pyrite in the matrix indicates deposition in the phreatic zone, followed by diagenetic alteration in the vadose environment and later exposure to arid conditions. The mineral composition of T_3^{2+3} , $\text{J}_3^{1,2}$ and $\text{K}_2^{2,3}$ bauxites also support their categorisation as vadose bauxites (D'Argenio and Mindszenty, 1995). In the T_3^{2+3} bauxites, however, there is no enrichment of the bauxitophilic elements Co, Cr, Ni, and V, which is due to their probable granitic source. Some minor content of Ni and Co occur in Mn oxides in $\text{J}_3^{1,2}$ bauxite. In all four profiles, there is no content of the above-mentioned trace elements as suggested by Maksimović (1988). The reason for the mismatch of some properties with the proposed classifications could be that depositional and diagenetic facies are closely related, but not necessarily identical, and bauxites undergo mineralogical and geochemical changes (D'Argenio and Mindszenty, 1995).

The bauxite profiles show systematic mineralogical differences that reflect varying degrees of diagenetic overprint and redox evolution. In the T_3^{2+3} , $\text{J}_3^{1,2}$ and $\text{K}_2^{2,3}$ profiles, böhmite is the dominant Al-bearing mineral, indicating dehydration of original gibbsite or amorphous Al hydroxides during diagenesis and/or low-water-activity conditions, whereas O_2 is characterised by kaolinite as the principal Al phase with subordinate diaspore, suggesting stronger silica influence and more advanced alteration of kaolinite. Kaolinite is the prevailing clay mineral in all profiles, and the association of hematite, goethite/lepidocrocite, and locally authigenic pyrite records fluctuating oxidising to mildly reducing conditions during bauxitisation and subsequent diagenesis.

Overall, the mineral assemblages indicate a progression from more hydrated precursor phases towards böhmite- and diaspore-bearing bauxites under increasingly dehydrating and locally redox-variable conditions.

5.2. Classification of bauxites

Based on Al_2O_3 , Fe_2O_3 , and SiO_2 contents, the analysed bauxites were classified into different groups according to Bárdossy (1982) (Fig. 11a). The T_3^{2+3} samples are mostly distributed from ferritic bauxite to bauxitic kaolinite, with the majority of samples in the bauxite field. The $\text{J}_3^{1,2}$ samples are mainly classified as laterites, kaolinitic bauxites, and bauxitic kaolinites; the $\text{K}_2^{2,3}$ samples as bauxites and kaolinitic bauxites; and the O_2 samples as laterites and bauxites. The differences between the analysed bauxites are also evident in the Cr-Ga-Zr diagram (Ozli, 1983) (Fig. 11b), in which the T_3^{2+3} bauxite samples are assigned to the granite area, the $\text{J}_3^{1,2}$ and $\text{K}_2^{2,3}$ bauxites to the basic/mafic rock area, and the O_2 bauxites to the intermediate igneous rock area. The source material close to granite composition for T_3^{2+3} and O_2 bauxites is also confirmed by tourmaline identified by SEM/EDS, Eu anomaly vs. $\text{TiO}_2/\text{Al}_2\text{O}_3$, and Ti/Cr diagrams (not shown here), where the other three bauxites are positioned close to UCC (MacLean et al., 1997; Mameli et al., 2007).

5.3. Weathering and environmental conditions

Evidence of variable Eh-pH conditions is provided by the changing values of Ce/Ce^* and La/Y (Fig. 12) in different sections of the T_3^{2+3} , $\text{J}_3^{1,2}$, and $\text{K}_2^{2,3}$ profiles (Ahmadnejad et al., 2017; Tomašić et al., 2021). In the T_3^{2+3} , $\text{J}_3^{1,2}$, and $\text{K}_2^{2,3}$ profiles, the different sections reached varying degrees of weathering according to the index of lateritisation (IOL), the $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio, and the Sm/Nd ratio (Fig. S5). The index of lateritisation, introduced by Babechuk et al. (2014) and defined as $\text{IOL} = 100 \times (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)/(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$, can be combined with the $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-Fe}_2\text{O}_3$ (SAF) plot (Schellmann, 1981, 1982, 1986, modified by Babechuk et al., 2014) and $\text{Sm}/\text{Nd}/\text{CIA}$ diagrams (Babechuk et al., 2014). However, the chemical index of alteration (CIA; Nesbitt & Young, 1984; McLennan, 1993) indicates highly weathered material in all profiles. The values are generally above 98, except for the $\text{J}_3^{1,2}$ profile, where they are around 90, and the two lowest samples from the T_3^{2+3} profile.

The T_3^{2+3} samples appear the least weathered due to their high SiO_2 content in both the upper and lower parts of the profile (Pod 01 – above kaolinitisation; Pod 02, Pod 09, Pod 10 – kaolinitisation; Fig. 13). However, between these layers, the degree of lateritisation varies irregularly, ranging from weak (Pod 04, Pod 07), through moderate (Pod 05, Pod 06, Pod 08), to strong lateritisation (Pod 03).

The La/Y ratio provides information about the environment in which the bauxite material was deposited. Based on this ratio, it is possible to infer the pH of the environment. If the La/Y ratio is less than 1, the depositional environment was acidic, while a ratio greater than 1 indicates deposition in a neutral environment (Radusinović et al., 2017). The Ce/Ce^* anomaly provides information about the oxidation–reduction conditions during deposition and diagenesis (Chen et al., 2022). Under oxidising conditions, Ce oxidises from the Ce^{3+} form to the Ce^{4+} oxidation state. A positive Ce/Ce^* value indicates oxidising conditions during deposition and diagenesis, while a negative value indicates reducing conditions in the environment (Esmaily et al., 2010).

According to the La/Y ratio, the entire T_3^{2+3} profile, except for sample Pod 02, shows values typical of acidic conditions with little variation. In contrast, Ce/Ce^* indicates variable redox conditions, with samples Pod 03 and Pod 09 showing no Ce anomaly. Samples Pod 04 and Pod 07, which are only weakly lateritised, exhibit the most oxidative (Ce/Ce^*) and the most acidic (La/Y) environments (Fig. 12).

The $\text{J}_3^{1,2}$ samples are the least weathered of all analysed profiles, as indicated by their slightly lower CIA and IOL values and their position in

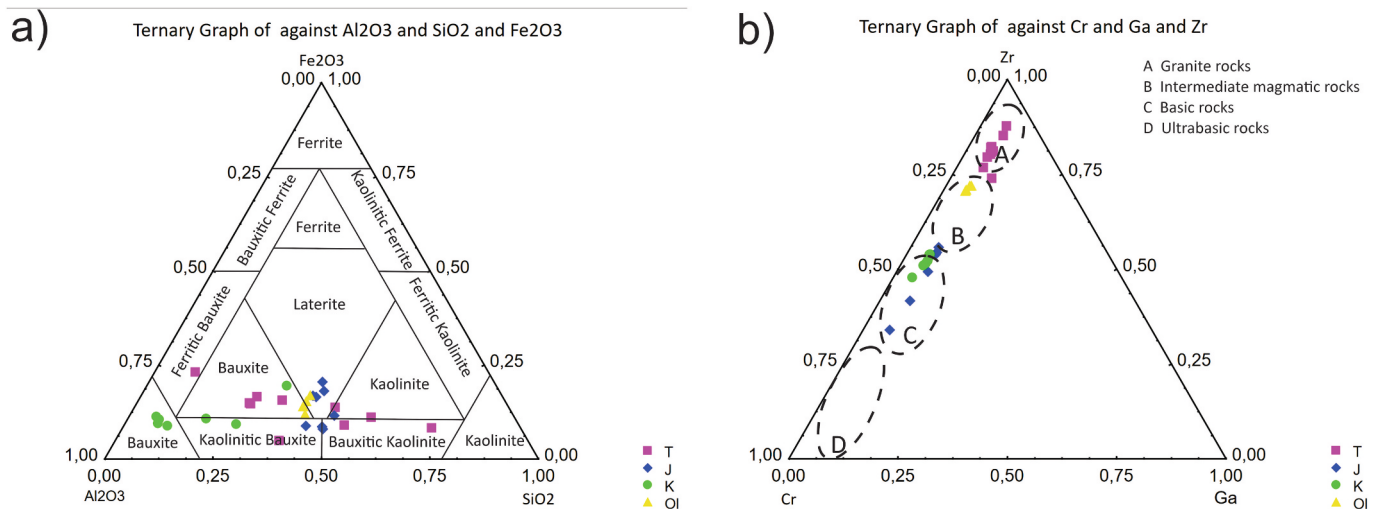


Fig. 11. Ternary diagrams: (A)—SiO₂-Al₂O₃-Fe₂O₃ after Bárdossy (1982) presenting mineralogical classification of investigated bauxites. T (T₃²⁺³) samples plot mainly in the bauxite field, while J (J₃²), K (K₃²⁺³), and Ol (Ol₂) span lateritic to bauxitic compositions.; (B)—Cr-Ga-Zr after Özlü (1983) showing classification of investigated bauxites T bauxites plot in the granite field, J and K in the basic/mafic field, and Ol in the intermediate igneous field.

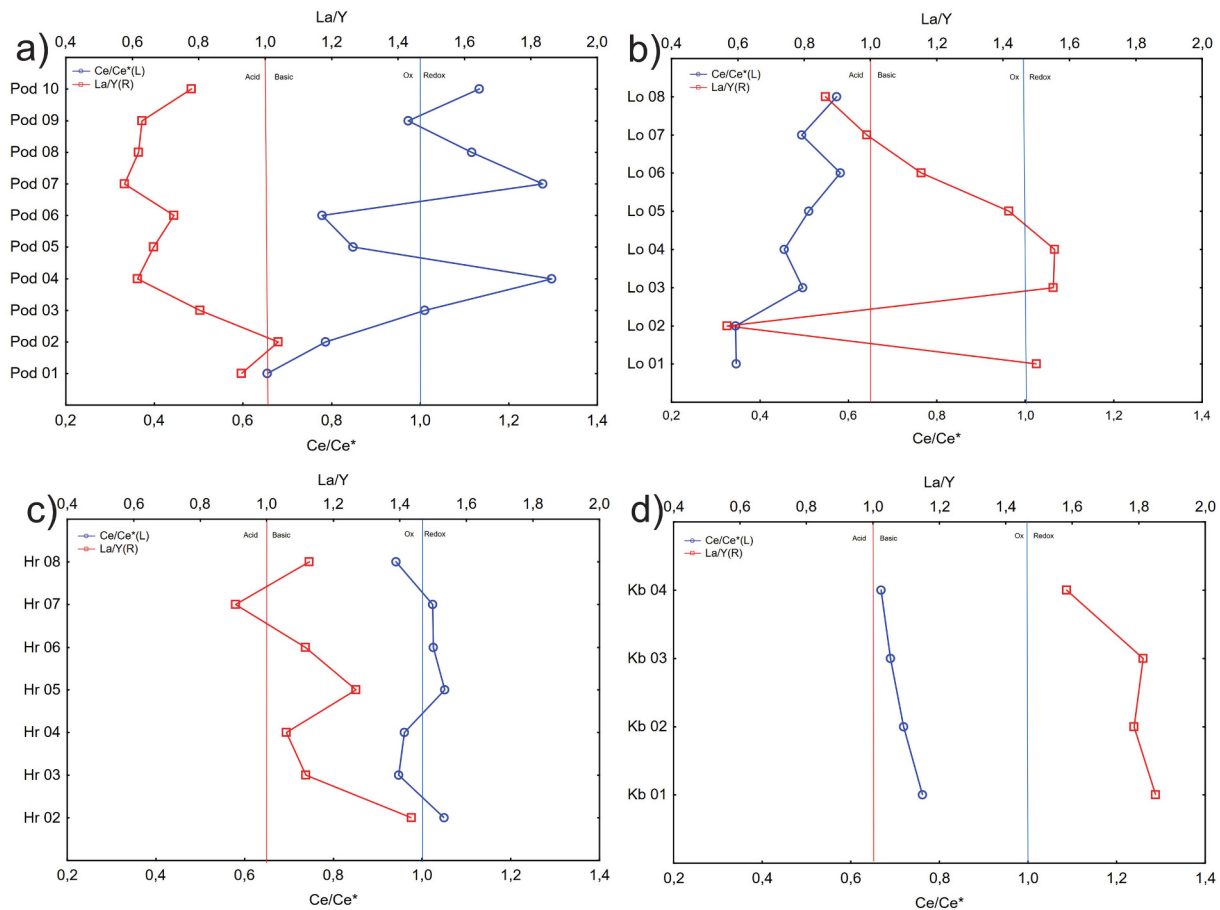


Fig. 12. La/Y ratio and Ce/Ce* values of investigated bauxites – a) Podlipa T₃²⁺³, b) Logatec J₃^{1,2}, c), Hrušica K₃²⁺³ and d) Kamniška Bistrica Ol₂. The T₃²⁺³ and K₃²⁺³ profiles record generally oxidizing weathering conditions with variable LREE enrichment, whereas the J₃^{1,2} and especially the Ol₂ profiles exhibit more pronounced Ce depletion coupled with increasing LREE/HREE fractionation. These differences suggest spatial variability in redox conditions and weathering intensity during lateritic profile development.

the SAF diagram (Fig. 13, Fig. S4). Samples with a slightly lower Al₂O₃/SiO₂ ratio are classified as kaolinitised (Lo 6, Lo 7, Lo 8). The uppermost sample, Lo 08, is labelled as silicified bauxite, while samples Lo 07 and Lo 06 are described as bauxite clay with an interbedded limestone lens;

all have elevated CaO content (Fig. 10b). All other samples are categorised as weakly lateritised, although the lowest sample, Lo 01, is described as oolitic limestone with a CaO content of up to 40%. Based on Ce/Ce*, the entire profile is the least oxidised (Fig. 12), with the two

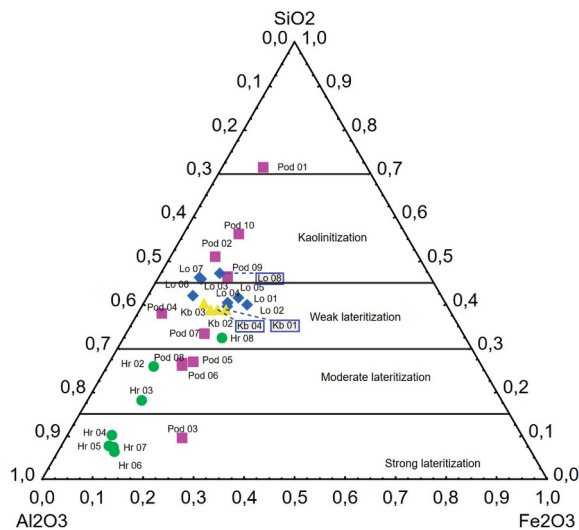


Fig. 13. SAF diagram of investigated bauxites after Bárdossy (1982). Most T_3^{2+3} , $J_3^{1,2}$ and Ol_2 samples plot within the weak lateritization field, indicating moderate silica depletion accompanied by enrichment in Al_2O_3 and Fe_2O_3 . Several T_3^{2+3} samples and the majority of $K_2^{2,3}$ samples are located in the moderate lateritization field, suggesting a more advanced weathering stage. The $K_2^{2,3}$ samples extend toward the strong lateritization field, reflecting pronounced silica loss and relative enrichment of iron and aluminum oxides.

lowest samples, Lo 01 and Lo 02, being the most reduced, and samples Lo 06 and Lo 08 being relatively more oxidised. From top to bottom, the La/Y ratio increases steadily, indicating increasing alkalinity, except for sample Lo 02, which formed in the most acidic environment of all the profiles analysed.

The entire $K_2^{2,3}$ profile consistently shows the highest degree of bauxitisation among all analysed bauxite profiles. From the central part, which shows the same degree of weathering, there is a continuous trend towards less weathered material at the top and bottom of the profile. However, the Eh-pH conditions are variable throughout the profile. There is a slightly negative Ce anomaly at the top and bottom of the profile in samples Hr 03, Hr 04 and Hr 08, and a slightly positive anomaly in the central part (Hr 05, Hr 06 and Hr 07) and in the lowest sample of the bauxitic breccia (Hr 02). In the latter case, the carbonate clasts influence the Ce anomaly. According to the La/Y ratio, the only sample that shows acidic conditions is Hr 07.

The Ol_2 profile exhibits fairly uniform, weak lateritisation. The La/Y ratio indicates the most basic pH conditions among the four profiles, though there are some variations within different parts of the profile. The Ce/Ce* ratio increases from the top to the bottom of the profile but consistently indicates a reducing environment. Although it contains both slightly oxidised and unaltered pyrite, the Ce/Ce* ratio is slightly higher than in the $J_3^{1,2}$ profile, where the pyrite is limonitised. The Sm/Nd ratio indicates a gradual transition from the less weathered upper part, composed of bauxitic clay, to the more weathered lower part, composed of bauxitic breccia.

The REE distribution patterns indicate variable degrees of LREE enrichment and fractionation among the investigated bauxite profiles, whereas HREE generally exhibit more conservative behaviour during weathering. The preferential enrichment of LREE is attributed to the combined effects of dissolution–reprecipitation processes, retention of REE-bearing accessory minerals (particularly monazite), and preferential adsorption onto secondary phases, especially kaolinite and Fe oxyhydroxides (Bau, 1999; Berger et al., 2014; Yang et al., 2019). The degree of LREE fractionation reflects differences in the intensity of REE redistribution during bauxitisation. Negative Eu anomalies across all profiles indicate preferential Eu depletion inherited from precursor

materials and subsequently preserved during weathering, whereas variations in Ce anomalies record redox-controlled redistribution through the oxidation of Ce^{3+} to relatively immobile Ce^{4+} under oxidising conditions (Bau, 1999; Balaram, 2019). In the Jurassic profile, pronounced REE enrichment at the carbonate geochemical barrier indicates that neutralisation of acidic weathering fluids promoted REE retention and precipitation of secondary REE-carbonate phases, highlighting the important role of carbonate rocks in controlling REE mobility and accumulation during bauxitisation (Mongelli et al., 2017).

5.4. Ree-bearing minerals and phases

The distribution pattern of LREE and HREE in the T_3^{2+3} profile is identical (Fig. 8a). The contents of LREE and HREE are highest in samples Pod 03, Pod 06, and Pod 09, although their degrees of weathering differ significantly. In the strongly lateritised sample Pod 03, SEM/EDS revealed corroded detrital monazite (Ce) and xenotime grains, as well as neoformed secondary authigenic cerianite (Ce) (CeO_2) on anatase, close to the contact with dolomite in the footwall and Carnian clastites in the hanging wall, as the main carriers of REE (Fig. 7a). Cerianite (Ce) crystallisation can be explained by the oxidation of Ce (Mongelli, 1997; Li et al., 2013), as there is a transition from a reductive environment above sample Pod 03 to a more oxidative environment further down the profile. Additionally, weathering of the profile under acidic conditions enabled the release of Ce and its fixation in cerianite (Ce) when the environment became less acidic (Liu et al., 2013; Mongelli et al., 2014). Strong lateritisation of the profile is also reflected in high contents of Al_2O_3 , Fe_2O_3 , TiO_2 , and Zr oxides (baddeleyite; Fig. 7d). Surprisingly, the contents of P_2O_5 are quite low; therefore, we assume that REEs are probably also associated with böhmite, hematite, goethite/lepidocrocite, ilmenite, anatase and Zr oxides (Fig. 8). The increased REE content may result from the adsorption of elements on the surfaces of clay minerals or minerals of aluminum oxides and hydroxides, and Fe-oxyhydroxides (Li et al., 2020; Mondillo et al., 2019), isomorphous replacement of the main elements in the Al-hydroxide crystal lattice (Li et al., 2013), or precipitation of authigenic minerals (Li et al., 2013; Maksimović and Panto, 1991). The sumREE content in Pod 03 approaches 1000 mg/kg, which could allow the formation of authigenic REE minerals (Maksimović and Panto, 1995). LREE (except Ce) preferentially incorporate into Al-hydroxides, while HREE preferentially incorporate into Fe-oxyhydroxides (Mondillo et al., 2019). Böhmite has higher adsorption efficiency than goethite due to its larger surface area and greater number of functional groups (Granados-Correa et al., 2011). The observed high Fe_2O_3 content suggests that scavenging by goethite is possible (Mameli et al., 2007), although reductive conditions and basic pH argue against it (Mondillo et al., 2019). According to the chemical composition of moderately lateritised Pod 06, böhmite and baddeleyite, and to a lesser extent Ti-bearing minerals, are probable carriers of REE. In the kaolinitised sample Pod 09, SEM/EDS inspection showed the presence of secondary authigenic xenotime and detrital monazite (Ce) grains, as well as agglomerated cerianite (Ce) (Fig. 7f), which is consistent with slightly elevated P_2O_5 contents (Fig. 10a). In samples Pod 02, Pod 03, and Pod 07, which have quite low sumREE, SEM/EDS also showed scarce corroded detrital monazite (Ce) (Fig. 6f, Fig. 7b, Fig. 7e) and smaller detrital xenotime (Fig. 6e) grains, indicating possible release of primary REE-bearing phases during weathering and their deposition in lower parts of the profile. Detrital monazite (Ce) and xenotime, together with tourmaline, correspond to a granitic source rock. Authigenic REE-bearing minerals formed during weathering of the bauxite, where pH was the dominant parameter controlling REE mobility (Li et al., 2013). Under acidic conditions, REE are removed from weathering products and are fixed by major scavengers under neutral to alkaline conditions (Karadağ et al., 2009). Therefore, the T_3^{2+3} bauxite was exposed to acidic conditions, which gradually changed to neutral/alkaline conditions that promoted REE adsorption and precipitation of REE-bearing minerals.

In $J_3^{1,2}$ samples, SEM/EDS confirmed the presence of secondary authigenic REE carbonates/oxides close to the contact with footwall limestone: calcioancylite (Nd) ((Ce,Ca,Sr)CO₃(OH,H₂O)) or cerianite (Ce) without Th (Fig. 5d, Fig. S1f), and lanthanite (Nd) and lanthanite (Ce) (La₂(CO₃)₃·8H₂O) (Fig. 5f, Fig. S2a). In addition to REE carbonates/oxides in sample Lo 01, some micron-sized monazite (Ce) and xenotime grains are present, some with corroded surfaces (Fig. 5e, Fig. 6a, Fig. 6b, Fig. S2b). In Lo 03, the LREE content increases slightly, while the HREE content decreases (Fig. 8b), but the sumREE is only slightly higher. SEM/EDS identified secondary authigenic cerianite (Ce), and small detrital monazite (Ce) (Fig. 6a) and xenotime grains. There is a change in Eh value from reducing to oxidising conditions between samples Lo 03 and Lo 02. In samples Lo 05 and Lo 06, some small monazite (Ce) grains were observed. The same association of LREE and HREE with CaO is observed in Lo 07, where a limestone lens is present, which is also reflected in the La/Y ratio, indicating a transition from acidic to basic environment. The REE carriers are detrital micron-sized monazite (Ce) (Fig. 6b), xenotime, florencite (La) (CeAl₃(PO₄)₂(OH)₆) (Fig. 6d) and goyazite (Fig. 6c). Although classified as limestone, the lowest sample Lo 01 is extremely enriched in LREE and HREE (Fig. 9b). This could be due to reductive conditions and a drastic change in pH favouring dissolution and mobility in the acidic section of sample Lo 02, and precipitation in the carbonate-rich alkaline environment of Lo 01, where the REE are bound in REE oxides (cerianite (Ce)) and REE carbonates (calcioancylite (Nd)).

Despite the high degree of bauxitisation in the $K_2^{2,3}$ profile, the LREE and HREE content throughout the profile is the lowest of all investigated samples, due to its basic source protolith. LREE and HREE contents are highest in the most weathered part of the profile (Hr 05), which is associated with böhmite, anatase, ilmenite, and zircon (Fig. 10c). SEM/EDS analysis revealed corroded detrital xenotime and monazite (Ce) grains, up to 10 µm in size (Fig. 5a, Fig. 5c, Fig. S1e). In addition, HREE contents are also enriched in the upper part of the most weathered section (Hr 07), where enrichment of Al₂O₃, TiO₂, and Zr also begins.

The LREE and HREE values show slight variations in the Ol₂ profile, with both most enriched in the upper and lower parts of the profile, where contact with carbonate probably acts as a geochemical barrier (Fig. 10d). The distribution of LREE and HREE is opposite to that of

Al₂O₃ and TiO₂, and only slightly follows Fe₂O₃, but follows P₂O₅ in the lower part. The Zr distribution in the centre of the profile is consistent with the LREE pattern, but not with HREE. SEM/EDS analyses revealed detrital monazite (Ce) grains from micron to several microns in size and occasionally corroded xenotime grains in samples Kb 01 and Kb 03 (Fig. S1c). In addition to detrital monazite (Ce) and xenotime, secondary authigenic cerianite (Ce) was identified in sample Kb 03. The presence of cerianite (Ce) indicates oxidising conditions at the top of the profile, which is supported by the Ce/Ce* ratio.

The conceptual model (Fig. 14) illustrates the redistribution of REE during progressive weathering of a generalized bauxite profile. Weathering of the precursor material releases REE from primary detrital minerals, which are subsequently transported downward by meteoric waters. Their mobility is primarily controlled by pH and Eh. Under acidic conditions, dissolution of monazite and xenotime mobilises both LREE and HREE, which may be adsorbed onto clay minerals, böhmite, and Fe oxyhydroxides or incorporated into authigenic REE minerals. Cerium behaves differently, as oxidation of Ce³⁺ to the less soluble Ce⁴⁺ promotes cerianite precipitation, producing positive Ce anomalies in oxidised horizons.

Carbonate-rich material at the base of the profile forms an effective geochemical barrier. Increasing pH, commonly accompanied by decreasing Eh, together with dissolved carbonate and abundant reactive mineral surfaces, promotes REE immobilisation through adsorption and precipitation, resulting in the accumulation of secondary REE carbonates and oxides near the bauxite–limestone contact. The model therefore emphasises weathering-driven REE release, downward transport, and pH–Eh-controlled sequestration as the principal processes governing REE redistribution and enrichment.

Assessment of contribution of REE-bearing minerals to the total REE budget (Bea, 1996) in bauxites from each location showed that in bauxites from all locations the estimated total contribution of monazite (Ce), xenotime, florencite (La), cerianite (Ce) and calcioancylite (Nd) to the total REE budget is relatively low, between 2 and 29%. It is highest in the $J_3^{1,2}$ bauxites (29%), followed by T_3^{2+3} bauxites (9%), $K_2^{2,3}$ bauxites (3%) and Ol₂ bauxites (2%). Secondary authigenic lanthanite contributes most (24%), followed by detrital monazite (Ce) (9%) and xenotime (6%).

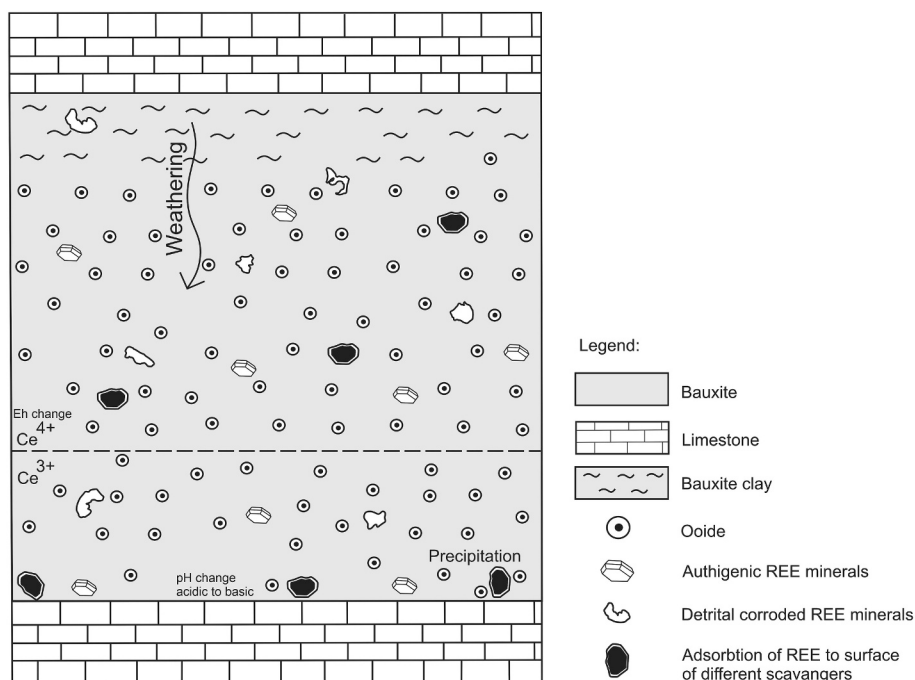


Fig. 14. Conceptual model of REE mobilisation and redistribution during bauxitisation above a limestone bedrock.

5.5. Comparison of REE content among bauxite profiles cross the wider Adriatic region

The wider Adriatic area is known for numerous bauxite occurrences developed between the Upper Triassic to the Miocene. Many of them have been studied for REE content (Fig. 15). REE averages for specific bauxite occurrences range from 218 mg/kg ($K_2^{2,3}$ Hrušica, Slovenia) to 1,145 mg/kg (Tošići-Dujići, Croatia).

However, it is important to note that these averages are based on different sampling approaches. Some averages represent the arithmetic mean of samples from one or a few exposed bauxite profiles at a single locality (e.g. Tomašić et al., 2021; Buccione and Mongelli, 2024, Bilić et al., 2025; this study), while others represent the arithmetic mean of bauxite occurrences of the same age across an entire country or a wider territory (e.g. Gamaletsos et al., 2019; Radusinović and Papadopoulos, 2021; Kovačević Galović et al., 2025).

Based on all reviewed data we can assume that the average bauxite REE content in the wider Adriatic region is approximately 580 mg/kg. Three out of four Slovenian bauxite profiles examined in this study, except for the $K_2^{2,3}$ bauxite profile at Hrušica, show REE contents above this average. However, comparison of bauxites from the same geological

period is more informative regarding to the paleogeographic context and tectonic setting at the time of formation.

REE content in Upper Triassic bauxites is reported only from Croatia and Montenegro. The Slovenian T_3^{2+3} bauxite profile in Podlipa, with an average REE level of 641 mg/kg, is among the more REE-enriched Triassic bauxites in the region. REE content is similar to the Vojnik-Maganik bauxites, which have an average REE level of 734 mg/kg (Radinović and Papadopoulos, 2021). Croatian Triassic bauxites in Kordun, Lika, and Dalmatia are very depleted in REE, with an average of only 263 mg/kg (Kovačević Galović et al., 2025). According to the geochemical parameters, all analysed Triassic bauxite occurrence have a felsic, continental crustal source. The main REE carriers in all three occurrences are detrital monazite and xenotime, with some secondary authigenic cerianite present in the T_3^{2+3} bauxite profile in Podlipa, and REE-carbonates in the Vojnik-Maganik Triassic bauxites. The Croatian Triassic bauxites in Kordun, Lika, and Dalmatia are described as “clayey bauxites” (Kovačević Galović et al., 2025), while Montenegrin and Slovenian bauxites fall within the classes of bauxites, ferritic bauxites and bauxitic kaolinite. This might explain the considerable differences in REE content in the region, as Fe-rich bauxites can adsorb REE in the Fe hydroxides and therefore contain much higher REE content compared to

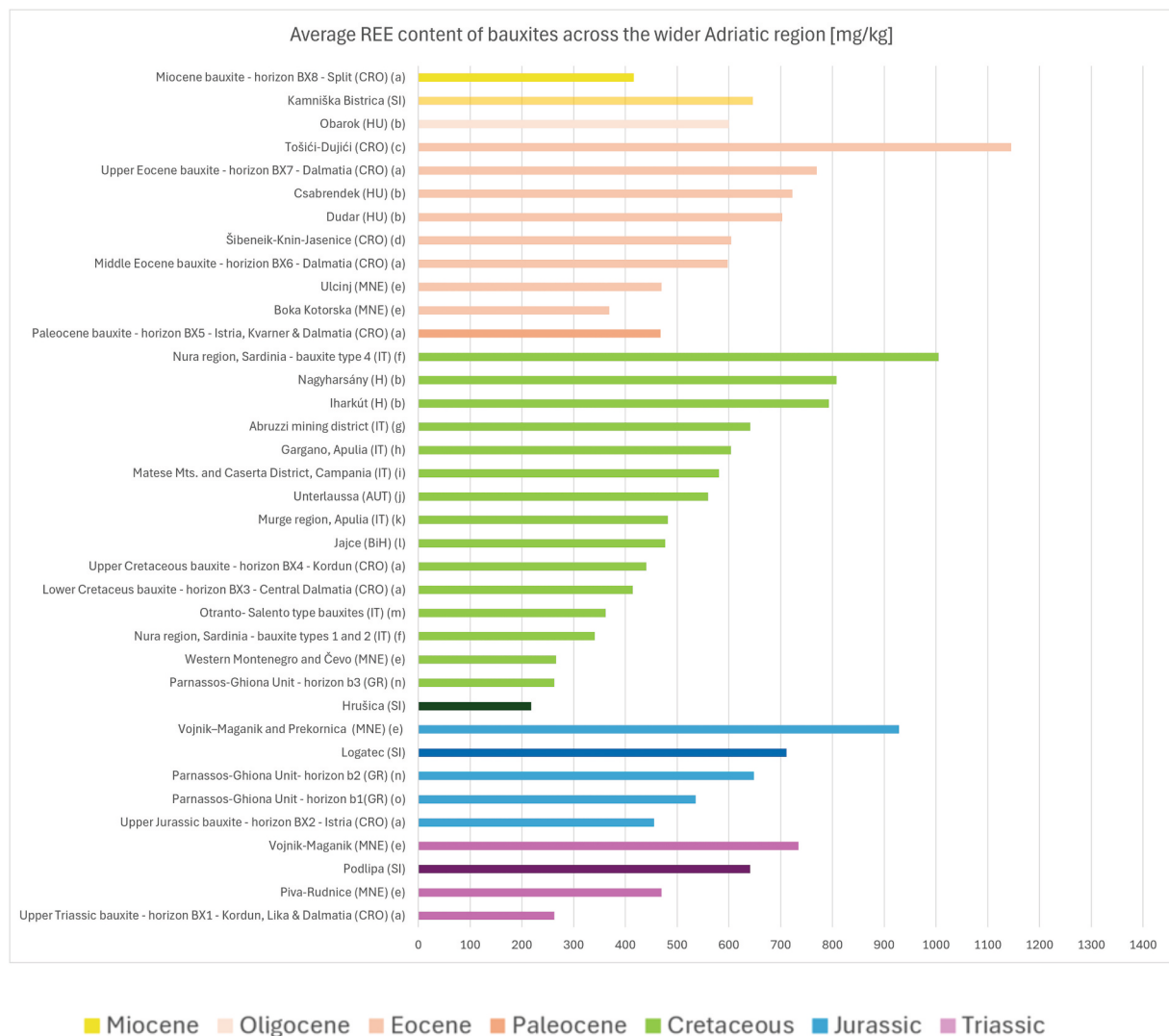


Fig. 15. Arithmetic mean of REE contents (calculated as the sum of La to Lu) of bauxites across the wider Adriatic region. Data sources: (a) Kovačević Galović et al. (2025), (b) Tomašić (2020), (c) Tomašić et al. (2021), (d) Brčić et al. (2023), (e) Radusinović and Papadopoulos (2021), (f) Mongelli et al. (2021), (g) Putzolu et al. (2018), (h) Mongelli et al. (2017), (i) Buccione and Mongelli (2024), (j) Hampl and Melcher (2023), (k) Mongelli et al. (2014), (l) Bilić et al. (2025), (m) Mongelli et al. (2016), (n) Gamaletsos et al. (2019), (o) Sofis et al. (2025).

other types of bauxites (Mondillo et al., 2019).

Jurassic bauxite horizons in the region display a similar pattern of REE content: the most REE-enriched are the Montenegrin Vojnik-Maganik-Prekornica bauxites, with an average of 929 mg/kg (Radusinović and Papadopoulos, 2021), followed by the Slovenian Logatec $J_3^{1,2}$ bauxite, with an average of 711 mg/kg. Greek b2 and b1, and Croatian BX2 bauxites, have lower REE content, with 648, 536 and 455 mg/kg respectively (Gamaletsos et al., 2019; Sofis et al., 2025; Kovačević Galović et al., 2025). Notably, the Logatec $J_3^{1,2}$ bauxite indicates basic rocks protolith and are classified as laterite and kaolinitic bauxite (Fig. 11). Montenegrin Jurassic bauxites, which are among the most REE-enriched bauxite occurrences in the Adriatic region, show more diverse bauxite sources, such as shales, UCC, and andesitic rock (Radusinović et al., 2017; Radusinović and Papadopoulos, 2021). Greek and Croatian Jurassic bauxite occurrences indicate mixed intermediate to basic parental material and a protolith close to UCC or cratonic sandstones (Kovačević Galović et al., 2025). In most Jurassic bauxite occurrences, authigenic REE minerals were detected alongside detrital monazite and xenotime, together with increasing REE levels towards the base of the bauxite profiles. This is also the case for Logatec $J_3^{1,2}$ bauxite, where a significant amount of secondary authigenic REE minerals such as calcioancylite (Nd), cerianite (Ce), –lanthanite (Nd), and lanthanite (Ce) was detected at the contact with highly weathered footwall limestones, as well as within a carbonate lens in the middle of the profile indicating precipitation of REE minerals at a geochemical barrier represented by limestone. These findings suggest REE-enriched parental material for Jurassic bauxites and significant REE remobilisation during in-situ diagenesis.

Cretaceous bauxite occurrences are among the most common and well-studied in the region. Generally, Cretaceous bauxite occurrences in the Dinaric domain have considerably lower REE contents than those in the Apennines, Eastern Alps, and Pannonian Basin (Fig. 14) which may indicate differences in the source material or bauxite evolution. The most REE-enriched bauxites are type 4 bauxites in the Nura region, Sardinia, with an average REE content of 1005 mg/kg (Mongelli et al., 2021) and Hungarian bauxites at Nagyarsány and Iharkút with 808 and 793 mg/kg respectively (Tomašić, 2020). Interestingly, the Slovenian $K_2^{2,3}$ bauxite profile at Hrušica has the lowest REE content not only among Cretaceous bauxites but also among all bauxite occurrences in the region. The source rocks of the $K_2^{2,3}$ Hrušica bauxites are identified as basic to intermediate magmatic rocks (Fig. 11). Generally, Cretaceous bauxites derived from basic to intermediate parent material show relatively lower REE content (e.g. Western Montenegro and Čevo bauxites in Montenegro (Radusinović and Papadopoulos, 2021) with 266 mg/kg REE, Jajce, BiH (Bilić et al., 2025) with 477 mg/kg and the Murge region in Apulia, Italy (Mongelli et al., 2014) with 482 mg/kg REE). However, the impact of basic rocks erosion cannot be excluded even for more enriched bauxite occurrences such as Nagyarsány and Iharkút in Hungary (Tomašić, 2020). Hrušica $K_2^{2,3}$ bauxite exhibits strong laterization (Fig. 11) and is classified as bauxite (Fig. 13). Parallels can be drawn with Montenegrin Cretaceous bauxites, which are also classified as bauxites and have very low REE content (Radusinović and Papadopoulos, 2021), and with Jajce, BiH bauxites, which are classified as ferritic bauxites and have moderate REE levels (Bilić et al., 2025). The most probable reason for the low REE content in Hrušica $K_2^{2,3}$ bauxite is depletion of REE during the bauxitisation process. As the lower parts of the Hrušica $K_2^{2,3}$ profile and its footwall do not show any REE enrichment, it is possible that the main phase of REE remobilization occurred elsewhere and that the bauxite material was subsequently resedimented to the current location, as also indicated by the breccia structure in the lower part of the bauxite profile.

Of the only two studied Oligocene bauxite occurrences in the region the Slovenian Ol_2 bauxite horizon in Kamniška Bistrica, with an average REE content of 646 mg/kg, has a slightly higher average REE content than the Hungarian Obarok bauxite profile which contains 600 mg/kg of REE (Tomašić, 2020). When comparing Paleogene bauxite occurrences

in general, the Ol_2 bauxite occurrence in Kamniška Bistrica ranks in the middle among all studied bauxite occurrences. Geochemical parameters indicate that the Kamniška Bistrica Ol_2 bauxite is derived from intermediate igneous rocks, exhibits weak laterization and is classified partly as bauxite and partly as laterite (Figs. 11 and 13). U-Pb dating of Obarok bauxites confirmed their Oligocene age and showed that the parent material originates from local Permian sources, as well as eroded rocks from the Eastern Alps, Bohemian Massif and volcanic ash from coeval volcanism in the region (Kelemen et al., 2017).

5.6. Economic significance

Karst-type bauxites are generally considered to be significantly enriched in REE (Borra et al., 2016). However, elevated REE concentrations alone do not necessarily indicate economic potential, either for bauxite mining or for REE extraction. The latter depends particularly on the mineralogical host phases of REE, which largely determine their metallurgical recoverability. REE can be bound to bauxite by water-soluble and ion-exchangeable phases, colloid precipitate phases or as mineral phases and each of them demands separate treatment.

During alumina production by the Bayer process, most REEs remain in the insoluble residue (red mud), resulting in a relative enrichment of REEs compared with the original bauxite ore (Borra et al., 2016). For example, red mud from Kidričevo, Slovenia, contains 804.1 mg/kg REE (Tomašić, 2020), red mud from Ajka, Hungary, contains 959.9 mg/kg REE (Tomašić, 2020), and red mud from the Podgorica disposal sites in Montenegro contains 1309.6 mg/kg REE (Radusinović and Papadopoulos, 2021).

The recovery of REEs from red mud is technologically challenging and may pose environmental concerns. Although REEs can be extracted by direct acid leaching, this process is often constrained by high acid consumption, the generation of large volumes of effluents, and the simultaneous dissolution of iron and other major elements, which complicates downstream processing (Borra et al., 2016). More advanced approaches involving iron removal prior to leaching or combined sulfation-roasting-leaching processes have been proposed to improve the selectivity and economic viability of REE recovery (Borra et al., 2016).

Uysal and Supriyatna (2026) discuss the simultaneous recovery of aluminium and REE from high-silica (>8 wt% SiO_2) bauxites using an integrated hybrid hydrometallurgical process. Unlike the Bayer route, which concentrates REE in red mud, integrated extraction approaches aim to recover aluminium and REE directly from the ore, potentially reducing waste generation and improving overall resource utilisation. If such processes become technically and economically feasible at industrial scale, abundant bauxite deposits traditionally regarded as uneconomic for alumina production due to elevated SiO_2 contents may still represent a potential source of both alumina and REE.

All studied Slovenian bauxite occurrences, with the exception of the Hrušica $K_2^{2,3}$ bauxite occurrence, are high-silica bauxites and therefore unsuitable for alumina production by the Bayer process. The relatively small size of the known deposits is likely to limit economic viability even when alternative processing routes are considered. Although these deposits are associated with specific stratigraphic horizons, most occurrences are lenticular and lack lateral continuity. Based on historical investigations, the largest estimated bauxite resource is at the Podlipa T_3^{2+3} bauxite occurrence, which contains approximately 277,000 t of bauxite ore distributed among several lenticular ore bodies (Rijavec et al., 1965). Resources at the Hrušica $K_2^{2,3}$ and Kamniška Bistrica Ol_2 bauxite occurrences are estimated at approximately 6,000 t (Lukacs and Buser, 1966) and 5,000 t (Kuhar and Štern, 1963), respectively. No resource estimate has been published for the Logatec $J_3^{1,2}$ bauxite occurrence. Consequently, even if future technological developments improve the recovery of aluminium and REE from high-silica bauxites, the currently known Slovenian occurrences would probably still be below the scale required for standalone mining and processing

operations. Their main significance therefore lies in their scientific value particularly for understanding stratigraphic relations, bauxite-forming processes and REE enrichment and as indicators of the potential for discovering new bauxite bodies along favourable stratigraphic horizons at greater depths.

6. Conclusions

This study presents an integrated mineralogical and geochemical characterisation of four karst bauxitic occurrences in Slovenia (T_3^{2+3} from Podlipa, $J_3^{1,2}$ from Logatec, $K_2^{2,3}$ from Hrušica-Nadrt, and Ol_2 from Kamniška Bistrica), elucidating their provenance, diagenetic evolution, and rare earth element (REE) behaviour. According to the Al_2O_3 - Fe_2O_3 - SiO_2 diagram, T_3^{2+3} samples are mainly classified as bauxites and, to a lesser extent, as ferritic to bauxitic kaolinite; $J_3^{1,2}$ samples as lateritic-kaolinite, bauxites, and bauxite kaolinites; $K_2^{2,3}$ samples as bauxites and kaolinitic bauxites; and Ol_2 samples as laterites and bauxites. Cr-Ga-Zr relations indicate granitic sources for T_3^{2+3} , basic/mafic for $J_3^{1,2}$ and $K_2^{2,3}$, and intermediate igneous for Ol_2 .

Böhmite, which predominates over kaolinite in the T_3^{2+3} , $J_3^{1,2}$, and $K_2^{2,3}$ profiles, was probably formed through diagenetic dehydration of gibbsite. Kaolinite formed epigenetically via SiO_2 -rich fluid circulation through böhmite silicification or by dehydration of gibbsite/böhmite. The prevalence of kaolinite over diasporite in the Ol_2 profile implies initial lateritisation. Textural indicators record multiple reworking and resedimentation events. Except for Ol_2 , which preserves phreatic characteristics (mineralogy, organic residues, irregular trace-element distributions), the occurrences formed predominantly in vadose environments. Elemental distribution through the occurrences profiles is uniform in $K_2^{2,3}$ and Ol_2 , variable in T_3^{2+3} , meanwhile $J_3^{1,2}$ bauxites display REE enrichment at the base, with reprecipitation of REE carbonates and/or oxides at the bedrock interface.

The highest REE contents occur in $J_3^{1,2}$ bauxite occurrence, while the lowest are found in $K_2^{2,3}$ bauxite occurrence. In all bauxites, the main REE carriers are detrital monazite (Ce) and xenotime, with subordinate secondary authigenic xenotime. Low P_2O_5 contents suggest possible REE adsorption on clay minerals and aluminium oxide/hydroxide surfaces. Secondary authigenic cerianite (Ce) was identified in T_3^{2+3} and Ol_2 bauxites, and secondary authigenic cerianite (Ce), calcioancylite (Nd) ((Ce,Ca,Sr) $CO_3(OH,H_2O)$), or cerianite (Ce), lanthanite (Ce), and lanthanite (Nd) ($La_2(CO_3)_3 \cdot 8H_2O$) in $J_3^{1,2}$ bauxites.

Compared to Mediterranean bauxites, the investigated bauxites, except $K_2^{2,3}$, have average REE enrichment, but are currently economically insignificant due to the small size of the occurrences, high silica, sporadic REE distribution, and the mineralogical diversity of carriers within the same profile.

Although most of the investigated Slovenian bauxite profiles are limited in thickness and lateral extent, they provide valuable site-specific case studies for examining REE behaviour during bauxitisation and subsequent weathering. The results identify the main processes and mineralogical phases involved in REE mobilisation, redistribution, and fixation. However, the limited size of the occurrences restricts the extrapolation of these findings to larger or genetically different bauxite deposits. Therefore, the proposed enrichment mechanisms should be regarded as applicable to the studied profiles and as a basis for comparison, rather than as a universal model for bauxite-hosted REE mineralisation.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.oregeorev.2026.107523>.

Data availability

Data will be made available on request.

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