

Aligning Croatia's national solid mineral resources classification system with UNFC: a methodological framework and case-based implications

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Abstract

Reliable and up-to-date information on mineral resources is an essential foundation for strategic decision-making and long-term mining project planning. In Croatia, solid mineral resources have traditionally been classified using the national ABC₁ system, which is not aligned with internationally recognised reporting frameworks. This study applies the United Nations Framework Classification for Resources (UNFC) to a representative group of Croatian exploitation fields. In the national regulatory context, this term refers to a formally defined project category used by the mining authority to describe the legal and operational status of the mining project. The analysed group includes active and non-active exploitation fields, historic exploitation fields, and examples characterised by temporary administrative irregularities, defined as situations in which mining activities continue under acquired rights, rather than under an active concession. Two complementary approaches were used: the ORAMA (2019) PROJECT (2019) decision-flow methodology and the direct application of the UNFC Guidance Europe (UNECE, 2022). Independent assessments on the non-active exploitation fields conducted by two experts, resulted in fully aligned UNFC classifications despite differences in analytical emphasis. This outcome demonstrates the reproducibility and robustness of the UNFC framework. An additional example illustrates the dynamic nature of the UNFC by showing how temporary changes in project status can influence the project maturity and assigned category. The results confirm that the UNFC provides a transparent, adaptable and harmonised framework suitable for integrating Croatian mineral resource data into national and European reporting systems. Rather than replacing the national system, this study demonstrates a practical and transparent pathway for UNFC implementation and interoperability with wider relevance beyond the Croatian context.

1. INTRODUCTION

Standardized classification of mineral resources is essential for ensuring transparency, comparability, and informed decision-making across jurisdictions. The data used in this study originates from national registers and official records maintained by the Croatian Geological Survey and the competent mining authority, and are specific to the Croatian regulatory context. Such datasets, particularly historical estimates and legacy exploration reports, are often not aligned with international reporting standards, resulting in inconsistent interpretations and limited comparability at the European and global level. To address this challenge, the United Nations Framework Classification for Resources (UNFC), provides a comprehensive, and internationally harmonized system for resources classification. The UNFC supports transparent and comparable resource reporting through a hierarchical structure based on three fundamental criteria: economic and social viability (E-axis), technical feasibility (F-axis), and the degree of geological knowledge (G-axis) (UNECE, 2019, 2021, 2022; CRIRSCO & UNECE, 2024; Fig. 1). This structure allows resources and projects at different stages of development to be evaluated within a single, coherent framework.

Importantly, the UNFC offers sufficient flexibility to accommodate both active mining operations and early-stage or non-active projects. Legacy resource data can therefore be expressed in UNFC terms without altering the underlying geological estimates, enabling consistent reinterpretation of historical information while preserving its original technical basis.

The UNFC framework is closely aligned with the objectives of the United Nations 2030 Agenda for Sustainable Development (UNITED NATIONS, 2015), particularly with respect to transparent, responsible, and long-term management of natural resources. By providing a harmonised approach to the classification of mineral resources and reserves, the UNFC supports informed decision-making relevant to several Sustainable Development Goals, including those related to responsible consumption and production, economic development, and resource efficiency.

In recent years, significant efforts have been undertaken to align the UNFC with existing international reporting standards and national classification systems. These include initiatives compatible with the CRIRSCO family of reporting codes, supported through formal Bridging Documents that define equivalence between different classification schemes

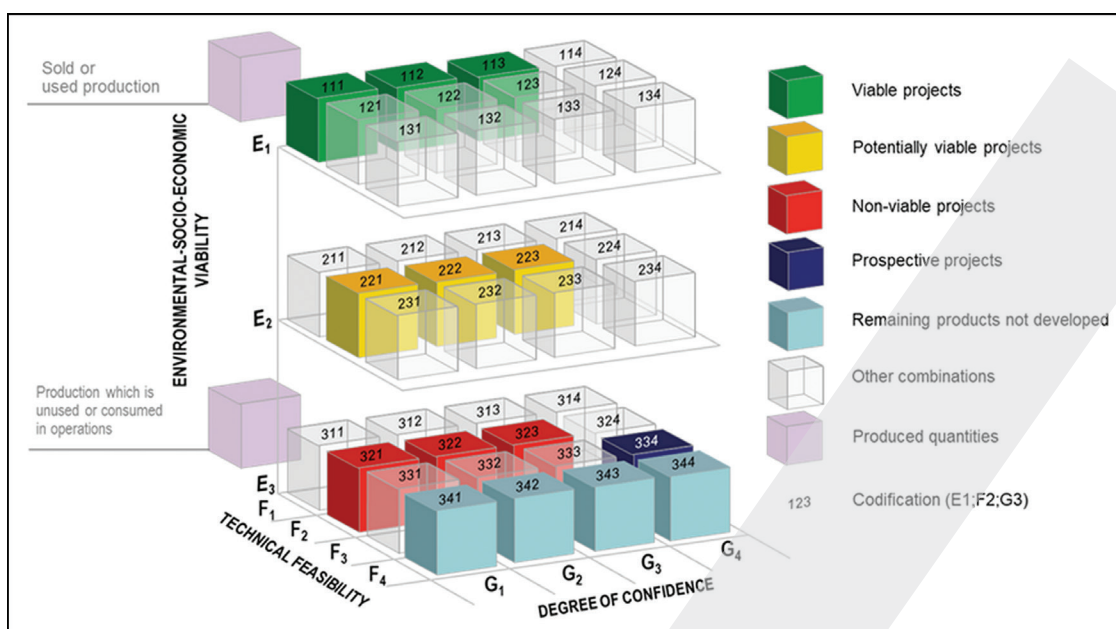


Figure 1. The UNFC Categories and example of classes of UNFC Guidance Europe (UNECE, 2022)

(UNECE, 2019; BIDE et al., 2022; CRIRSCO & UNECE, 2024; UNECE, 2025). One of the most widely applied frameworks in the mining sector is the CRIRSCO Template (CRIRSCO & UNECE, 2024), which ensures consistency and transparency in public reporting of exploration results, mineral resources, and mineral reserves. A key element of this system is the Competent Person concept, which underpins the credibility and accountability of reported estimates. Resources reported under CRIRSCO-based systems can be translated into UNFC categories using established equivalency mappings, allowing interoperability between classification frameworks (Table 1).

At the European policy level, the EU Critical Raw Materials Act (CRMA, 2024) frames the use of harmonised and internationally recognised reporting systems as part of strategic raw materials governance. Within this context, the UNFC is increasingly regarded as a practical classification tool that supports resource management, reporting, and strategic decision-making, rather than as a purely conceptual framework.

Against this background, Croatia represents a relevant case study for UNFC implementation. Solid mineral resources in Croatia have traditionally been classified using the national ABC₁ system, which remains deeply embedded in regulatory practice and historical datasets. While effective at the national level, this system limits international comparability and

integration with European reporting initiatives. Applying the UNFC therefore offers an opportunity to improve the transparency, consistency, and interoperability of Croatian mineral resource data.

This paper explores the application of the UNFC framework within the Croatian geological and regulatory context. Through selected case studies representing different project types and administrative statuses, the study demonstrates how the UNFC can be used to reinterpret existing resource data, support consistent classification outcomes, and enhance strategic resource planning. The approach highlights both the benefits and the practical challenges associated with integrating the UNFC into a national classification system, providing insights of broader relevance beyond the Croatian case. To improve manuscript readability, several supporting tables containing extended comparative information are provided in the Supplementary Material (Suppls. S1–S11).

2. METHODOLOGY

2.1. Study area

The study area comprises the Republic of Croatia and its immediate regional surroundings. For comparison of classification systems, five neighbouring countries are included: Austria, Slovenia, Hungary, Serbia, and Bosnia and Herzegovina. Within Croatia, the analysis focuses on selected

Table 1. Simplified Mapping of CRIRSCO Template to UNFC-2009 Classes and Categories (CRIRSCO & UNECE, 2024).

CRIRSCO Template		UNFC-2009 minimum Categories			UNFC-2009 Class
Mineral Reserve	Proved	E1	F1	G1	Commercial Projects
	Probable	E1	F1	G2	
Mineral Resource	Measured	E2	F2	G1	Potentially Commercial Projects
	Indicated	E2	F2	G2	
	Inferred	E2	F2	G3	
Exploration Results		E3	F3	G4	Exploration Projects



Figure 2. An overview map of the study area (modified after KORBAR, 2009). EPSG: 4326. Coloured hatched polygons (black, red, blue, orange, and purple) indicate the Republic of Croatia neighbouring countries included for comparative analysis (respectively Austria, Slovenia, Hungary, Serbia, and Bosnia and Herzegovina). The white dots represent major cities within the Republic of Croatia (Zagreb, Osijek, Rijeka, and Split). Coloured points (red, beryl green, magenta, orange, tourmaline green, and yellow) mark the locations of selected exploitation fields discussed here (the “Podevčevo”, “Rečica”, “Kruševo”, “Mamutovac”, “Krste Radas”, and “Vranjkovići” fields, respectively), which are distributed across the main geological regions of Croatia (External Dinarides and the Pannonian Basin).

exploitation fields representing different operational statuses as defined by the applicable Croatian Mining Act (2025; Fig. 2).

2.2. Review of the national legal framework

Under the applicable Croatian Mining Act (REPUBLIC OF CROATIA, 2023), reserves of solid mineral raw materials are classified into categories A, B, and C₁ based on the degree of exploration, the level of geological knowledge of the deposit, and the accuracy of reserve estimation, as defined by the applicable Ordinance on the Determination of Reserves and Exploitation of Mineral Raw Materials (REPUBLIC OF CROATIA (2022)). Reserves are categorized as: category A – confidence in exploration of more than 90% accuracy, category B – confidence in exploration of between 80–90%, and category C₁ – confidence in exploration of between 70–80%. Category C₂ refers to potential mineral reserves estimated on the basis of geological and geophysical data that are partially verified by exploration work or have been determined by analogy with studied parts of the deposit, in accordance with the provisions of this Regulation (hereinafter referred to as mineral resources). Mineral resources in category C₂ are not

confirmed by the resolution of the commission for determining reserves and are only used as an indicative character.

Based on their exploitation potential, reserves of mineral raw materials are further classified into balance, off-balance, and exploitable reserves of mineral raw materials, depending on the feasibility of their exploitation (applicable Ordinance on the Determination of Reserves and Exploitation of Mineral Raw Materials (REPUBLIC OF CROATIA (2022)). When classifying a Project using the UNFC, only balance and off-balance reserves will be reported, as exploitable reserves are derived from balance reserves (and have the same UNFC code). To facilitate later comparisons, it is important to first clearly define the key

Table 2. Division of Projects (exploration and exploitation) according to the national Mining Authority as listed in the register of Exploitation Fields for Mineral Raw Materials.

Project type	Exploitation field	Exploration area
1	Active with valid concession	Active
2	Active with invalid concession	Active
3	Non-active	Non-active
4	Deleted	Deleted
5	Requested	Requested

terms from Table 2. While these definitions are discussed in the applicable Croatian Mining Act (REPUBLIC OF CROATIA, 2023), it is important to revisit them to ensure clarity and consistency within the context of this study.

An active exploitation field with valid concession is a designated area on land and/or at sea defined by its boundary coordinates, where the exploitation of mineral raw materials is required to take place. The field is established by the Mining Authority in accordance with the extent of the confirmed balance reserves of mineral raw materials and the location conditions specified in the valid location permit issued by the authority responsible for spatial planning. An active exploitation field with invalid concession designates areas where exploitation is prohibited by law or subordinate regulations (e.g., changes to spatial plans, protected coastal zones, etc.), but where a mining company has already been granted, a mining concession, or an approval for mining activities under previous regulations prior to the prohibition. The company may continue exploitation unless the Republic of Croatia or the relevant local/regional government authority issues a decision to revoke the concession and delivers that decision to the authority responsible for mining. This typically applies to exploitation fields operating under so-called "acquired rights," meaning they were granted approval for exploitation during the era of the former state (former Yugoslavia, ex YU). One example is an exploitation field that was granted a concession in the 1980s, valid until 2028. Consequently, it has not obtained all the currently required legal permits, particularly those related to environmental and nature protection, but it does hold a valid operational permit. Non-active exploitation fields for mineral raw materials are exploitation fields where mining activities have been permanently suspended, but no measures have been implemented to prevent potential hazards to people, property, nature, and the environment. These fields have not been deleted from the Register of Exploitation Fields for Mineral Raw Materials. Deleted exploitation fields for mineral raw materials are those fields where mining activities have been permanently suspended and which have been removed from the aforementioned register. A requested exploitation field in Croatia is an area on land or at sea where a mining entity applies for permission to exploit mineral raw materials. The requested area is defined by its boundary coordinates and is subject to a formal application process. The approval for exploitation is granted by the relevant authorities after a public tender, based on the availability of confirmed mineral reserves and the environmental and legal requirements. Once approved, the mining entity is granted a concession to begin exploitation activities.

Regarding exploration areas, an active exploration area for mineral raw materials, as defined by the applicable Mining Act, is a bounded area on land and/or at sea, delineated by the coordinates of its boundary points. The area is designated by the authority responsible for mining through a resolution issued following a public tender, for the purpose of exploring mineral raw materials with the intent of granting a concession for exploitation. A non-active exploration area refers to a designated area where exploration activities have been

temporarily or permanently suspended. There may be various reasons that these areas may no longer be actively explored, such as a lack of resources, changes in legal or environmental conditions, or the completion of previous exploration work. However, they remain officially recorded as exploration areas and have not been removed from the relevant register. A deleted exploration area refers to a designated area where exploration activities were once planned or approved but has been permanently removed from the official register. This typically occurs when exploration is no longer allowed in that area, or when the area has been revoked or cancelled by the relevant authorities. A requested exploration area is a designated area on land or at sea where a mining entity applies to explore mineral raw materials. The area is defined by its boundary coordinates and requires approval from the relevant authorities after a public tender. Once granted, the approval allows the entity to explore the area, with the goal of discovering and assessing mineral resources, potentially leading to a concession for exploitation.

The locations of all exploitation fields and exploration areas are publicly accessible through the WEBGIS portal maintained by the mining authority (MINISTRY OF ECONOMY, 2025).

2.3. Decision flow tools and direct use of the UNFC Guidance Europe

Here, the framework and tools developed as part of the European Union Optimising quality of information in raw materials data collection across Europe (ORAMA, 2019), were employed to standardize the classification of mineral resource data. The project highlighted the importance of harmonising national resource data with international frameworks. Europe continues to face significant challenges related to the heterogeneity of reporting systems, fragmented institutional responsibilities, and varying levels of transparency (ORAMA, 2019), particularly in Southeast Europe. Integration into European raw materials initiatives, such as the Geological Service for Europe (GSEU, 2022–2027), depends on both methodological alignment and institutional readiness. Building on this European perspective, BIDE et al. (2019, 2022) emphasise that the UNFC is not only a technical classification system but also a policy-oriented tool designed to bridge national practices with international standards. Their analysis shows that countries adopt different entry points into the UNFC depending on their historical legacies and institutional capacities (Table 3).

As part of the Geological Survey of Europe project (GSEU, 2022–2027), the Croatian Geological Survey actively participated in the capacity-building programme on the United Nations Framework Classification for Resources (UNFC). A series of "Train the Trainers" workshops were organised under the European Centre of Excellence on Sustainable Resource Management (GSEU, 2022–2027), providing structured training across three progressive levels. Throughout this process, The Guidance for the Application of the United Nations Framework Classification for Resources (UNFC) for Mineral and Anthropogenic Resources in Europe (UNECE, 2022) was applied directly.

Table 3. The UNFC experience of the neighbouring states of Hungary, Slovenia, Serbia, Bosnia and Herzegovina, and Austria.

Country	UNFC experience
Hungary	Over the past decade, Hungary has advanced the alignment of its national classification system with the UNFC. Both UNFC 2009 and 2019 have been translated into the Hungarian system and published, enabling their consistent use across industry, academia, and administration. A bridging document has been prepared, mapping national categories and CRIRSCO-type disclosures (JORC, 2012; PERC, 2021) into UNFC codes (SARA, 2022, Decree No. 20/2022, I.31.).
Slovenia	The Slovenian initiative has produced substantive products. A bridging document now provides clear guidance for converting Slovenian classifications into the UNFC categories. This has enabled integration of the Slovenian mineral resource data into the Mining Registry Book (GeoZS, 2025), an online platform that collects annual reports from concessionaires.
Serbia	An important step has been the gradual integration of the PERC and JORC standards into the Serbian reporting system. This development facilitates the preparation of exploration results, mineral resources, and mineral reserves by Competent Persons and supports their translation into the UNFC codes (ILICH & VUKAS, 2016; VUKAS, 2024).
Bosnia and Herzegovina	No formal UNFC-assessable results are available to date. National reports primarily provide production statistics and concession data but do not translate resource and reserve figures into internationally comparable categories. Unlike Slovenia, Hungary, or Serbia, Bosnia and Herzegovina has not tested the UNFC on case studies, nor has it developed pilot projects for specific commodities.
Austria	Through Geosphere Austria, the country participates in the GSEU project, where the UNFC categories are used to harmonize data on energy and raw materials at the European level. Pilot studies include non-metallic raw materials such as magnesite and talc, metallic ores in historical mining districts, and geothermal energy projects.

For active exploitation fields with valid concessions and non-active exploitation fields, a dual-method approach was applied for UNFC bridging. The first step relied on the structured decision framework developed within the ORAMA PROJECT, using decision flow tools (ORAMA, 2019), while the second step involved direct interpretation in accordance with the UNFC GUIDANCE EUROPE (2022). This approach ensured systematic and transparent assignment of each project to the appropriate UNFC category, based on clearly defined decision criteria. For an active exploitation field with invalid concession and non-active exploitation fields, the UNFC bridging procedure relied only on a direct interpretation of the official UNFC Guidance Europe (UNECE, 2022). Exploration areas were assessed following the same conceptual principles as exploitation fields, while accommodating for the specific characteristics of early-stage mineral projects. These projects had quite different levels of data and high levels of uncertainty, typical for exploration phases. The bridging approach used for handling data in exploration areas was also applied to requested exploitation fields, to ensure consistency across project stages. Deleted and requested projects can be treated as historical mines, and as exploration areas, respectively. For these types of mining areas the direct application of the UNFC framework is sufficient and straightforward, and no additional case examples were examined.

2.4. Experiences of the neighbouring states and data analogy

Across Europe, countries have taken very different routes for converting their mineral resource inventories to the United Nations Framework Classification for Resources (UNFC; Table 3). Neighbouring countries that once relied on the ABC₁ system have determined how legacy data can be translated, while Austria has been able to build directly from CRIRSCO-based definitions without the complexity of historical categories.

3. RESULTS

3.1. Decision flow tools

3.1.1. An active exploitation field with a valid concession

An example of an active exploitation field with a valid concession is the brick clay project of “Rečica”, located in Karlovac County (Fig. 3). The exploitation of brick clay at this site began as early as 1954 and has continued to the present day. The deposit is situated within the “Crna Mlaka” basin, and is primarily composed of Quaternary clay-rich sediments interbedded with layers and lenses of sands and fine-grained conglomerates, along with younger Neogene sands. Geological investigations have been conducted over several decades, in 1986, 1996, 2003, 2007, 2010, and most recently in 2020, included a drilling program with a total drilling length of 561.3 metres in 52 boreholes. The most recent official decision confirming the quantity and quality of the brick clay reserves was issued in 2021. According to this decision, the reserves were classified into categories A, B, and C₁, in line with the national classification system. By applying the UNFC methodology, the project is classified as a viable project with the numerical code E1 F1.1 G1 (GIZDAVEC et al., 2023).

3.1.2. Non-active exploitation field

No mining activity is currently being carried out within the non-active gypsum exploitation field of “Vranjkovići”, although several exploration campaigns were conducted between 1973 and 2020 (Fig. 4). Exploration drilling was undertaken in 1998 and 2000, totalling a length of 40 metres with accompanying sampling. The surface area of the exploitation field is 15.75 ha, and exploitation ceased before the recorded reserves of gypsum were extracted. Based on the available exploration data and the historical record, the field was assigned to category G2, reflecting a moderate level of geological confidence. Due to the absence of verified data

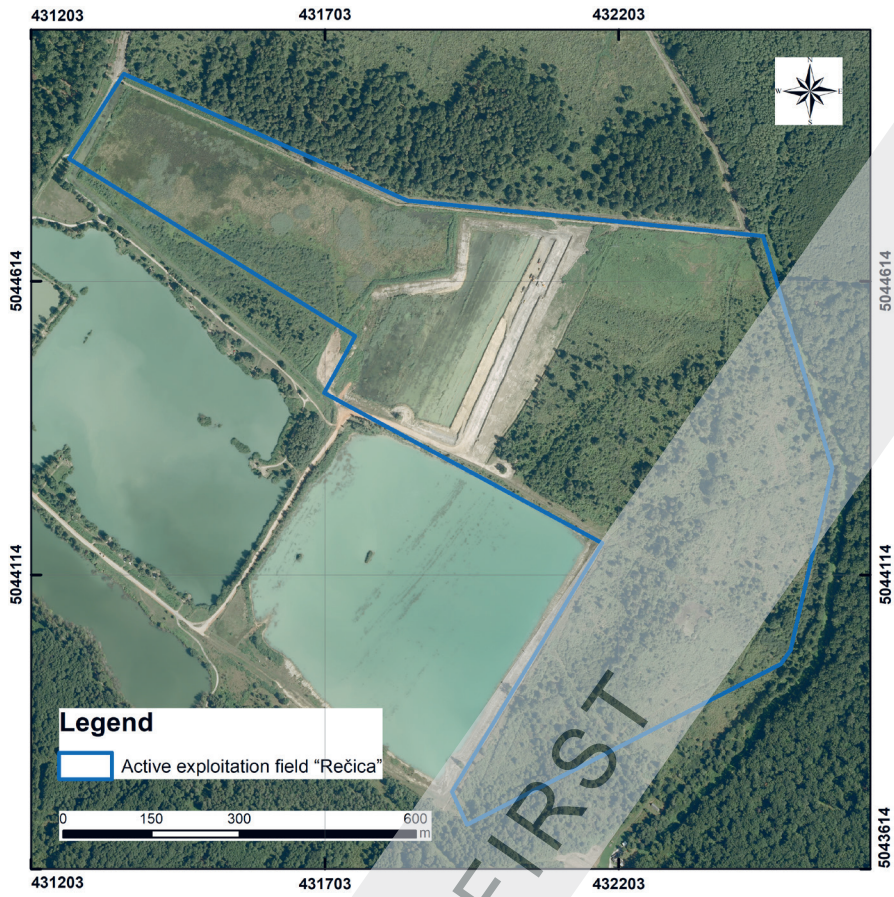


Figure 3. Spatial position of the active exploitation field "Rečica" (EPSG:3765)

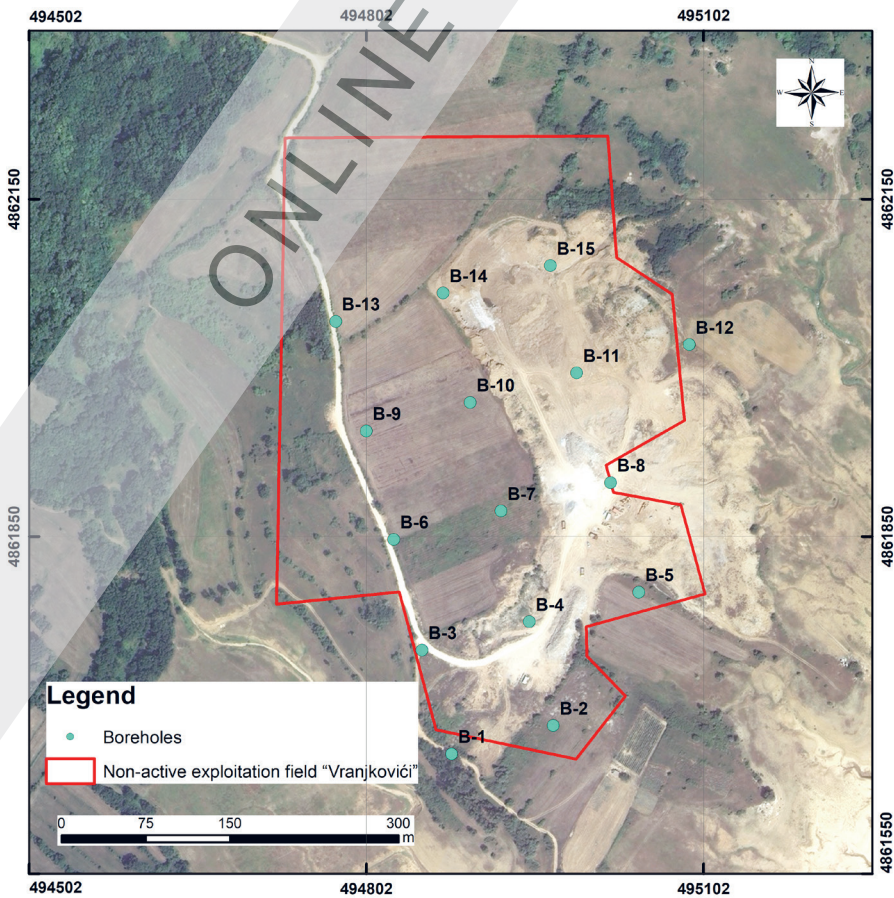


Figure 4. Spatial distribution of the non-active exploitation field "Vranjkovići" and exploration boreholes (EPSG:3765)

regarding technical feasibility and environmental, social, and economic conditions, the project was also placed into categories F2 and E2 respectively. In accordance with the

UNFC system, the project would therefore be classified as a potentially viable project, with the numerical code E2 F2 G2 (GIZDAVEC et al., 2023, Figs. 5–8).

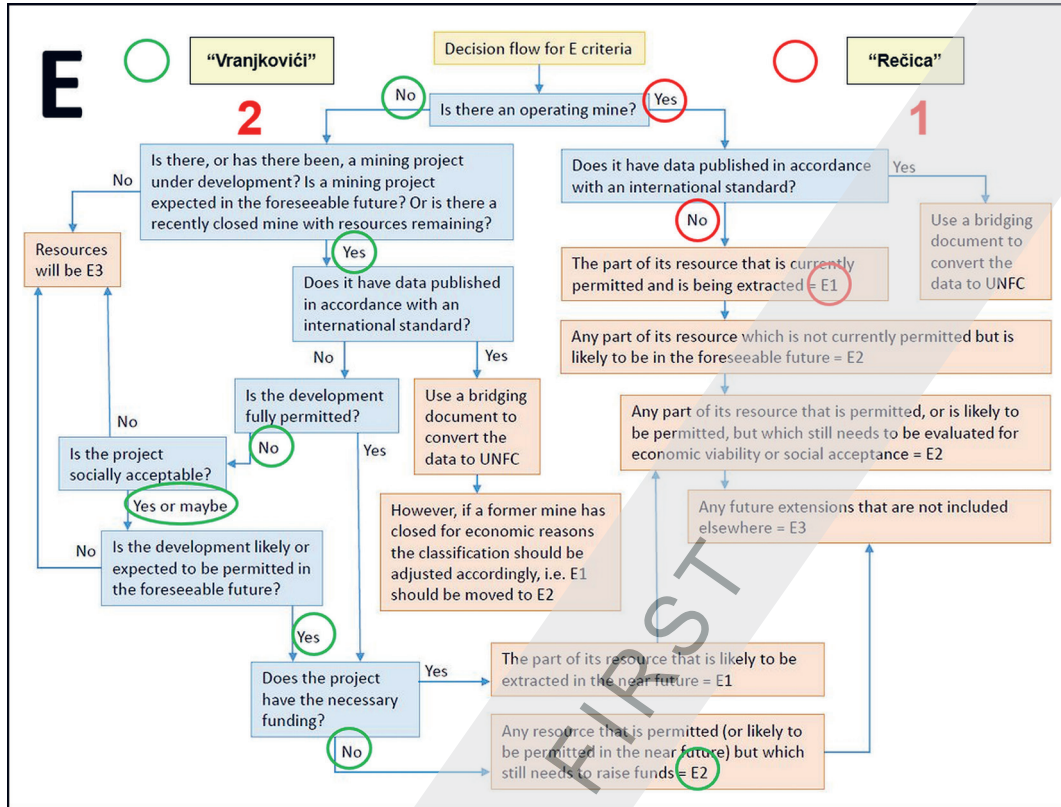


Figure 5. The decision flow for the E criterion for the "Rečica" and "Vranjkovići" exploitation fields (modified according to BROWN et al., 2019; GIZDAVEC et al., 2023)

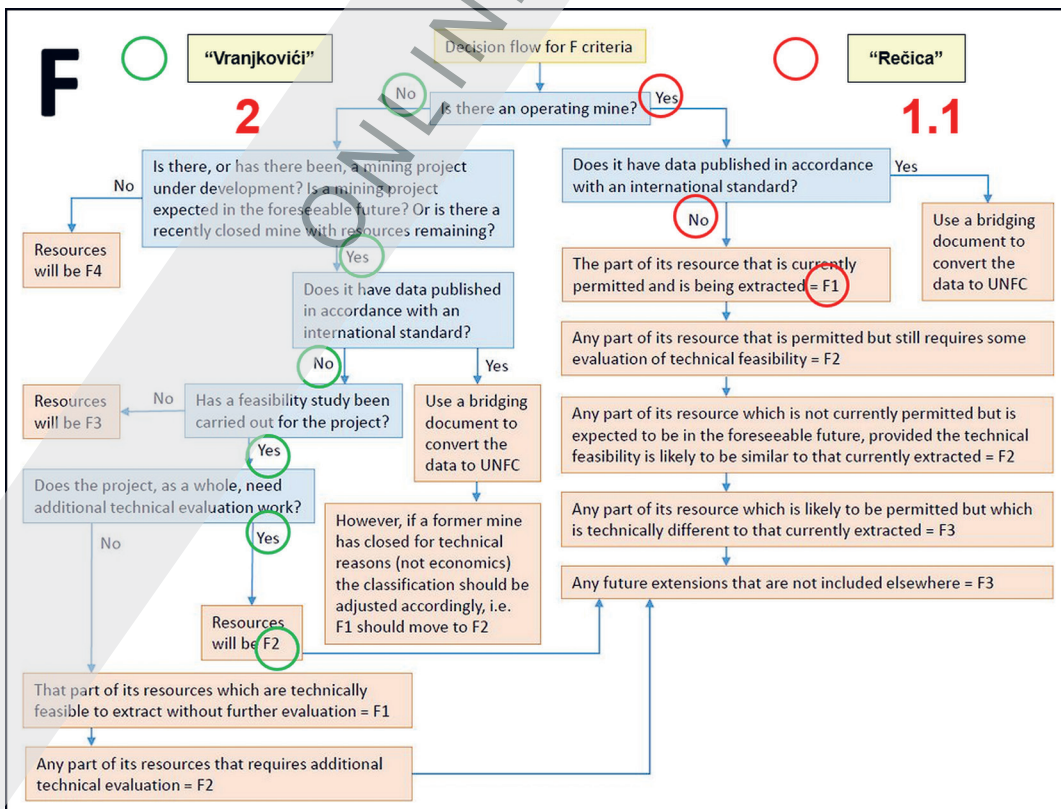


Figure 6. The decision flow for the F criterion for the "Rečica" and "Vranjkovići" exploitation fields (modified according to BROWN et al., 2019; GIZDAVEC et al., 2023)

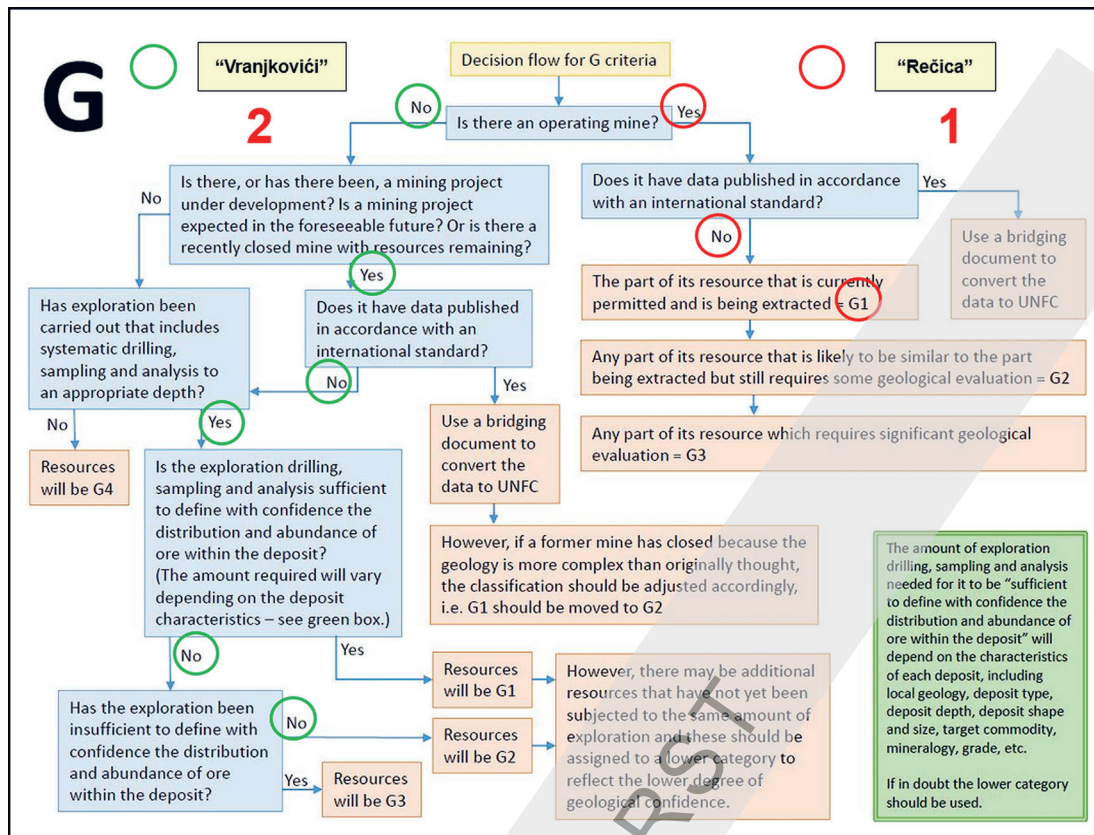


Figure 7. The decision flow for the G criterion for the “Rečica” and “Vranjkovići” exploitation fields (modified according to BROWN et al., 2019; GIZDAVEC et al., 2023)

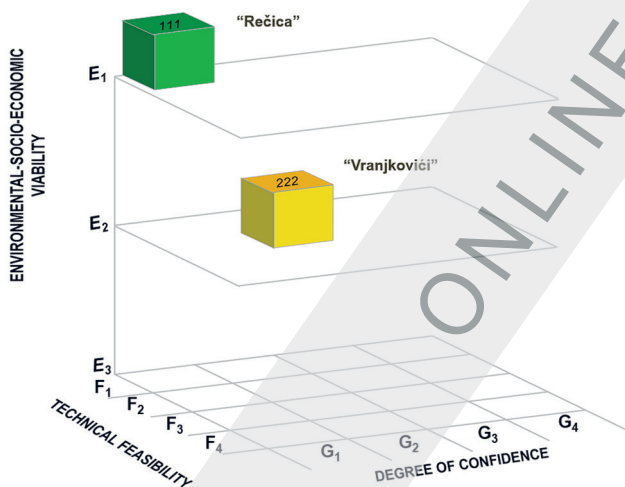


Figure 8. UNFC categories for the exploitation fields “Rečica” and “Vranjkovići”

3.2. Direct use of the UNFC GUIDANCE EUROPE

3.2.1. Active exploitation field with valid concession

The “Kruševo” active exploitation field, operating under a valid concession, covers 431.67 hectares, while confirmed reserves of all the identified mineral raw materials are confined to an area of 75 hectares (KRASIĆ, 2023). Bauxite, carbonate mineral raw materials for industrial processing, and crushed stone aggregates are currently extracted (Fig. 9). The bauxite is utilised in the cement industry rather than for aluminium production. The bauxite deposits of “Kruševo” are well documented in the literature (SAKAČ, 1961).

Within the confirmed reserve area, there are four bauxite deposits (“Stari gaj I”, “Stari gaj II”, “Blizanac V”, and “Blizanac IV”). Several additional bauxite deposits occur within the “Kruševo” exploitation field, but only off-balance reserves have been determined for them. In deposits with confirmed exploitable reserves, the bauxite is predominantly of hydragillite composition (hydragillite 60–70%, gibbsite 10–15%) and only rarely of hydragillite–böhmitic composition. The quality of bauxite is consistent and generally very good on average. The coefficient of variation for the aluminium and silicon components within each individual deposit is low and rarely exceeds 5%. The silicon module is mostly significantly higher than 7, which is taken as the threshold value for bauxite quality. The remaining part of the exploitation field is planned for reclamation.

Regarding project history, the former mining company DALMATINSKI RUDNICI BOKSITA d.o.o. Obrovac was granted exploitation rights for the bauxite in the then exploitation field “Kruševo” by a decision in 1972. Before that, detailed geological surveys were conducted by the Institute for Geological Research in Zagreb. Bauxite exploration conducted from 1982 to 1987 included standard methods used at the time, which defined specific deposits and involved exploration-geological drilling. Bauxite exploitation continued until the early 1990s, but it is poorly documented for five years, due to wartime events in the area. Additional exploration was carried out in 2005 when 15 exploration boreholes were drilled with a total length of 1,110 m. From December 2006 to August 2007, eight more exploration boreholes were drilled

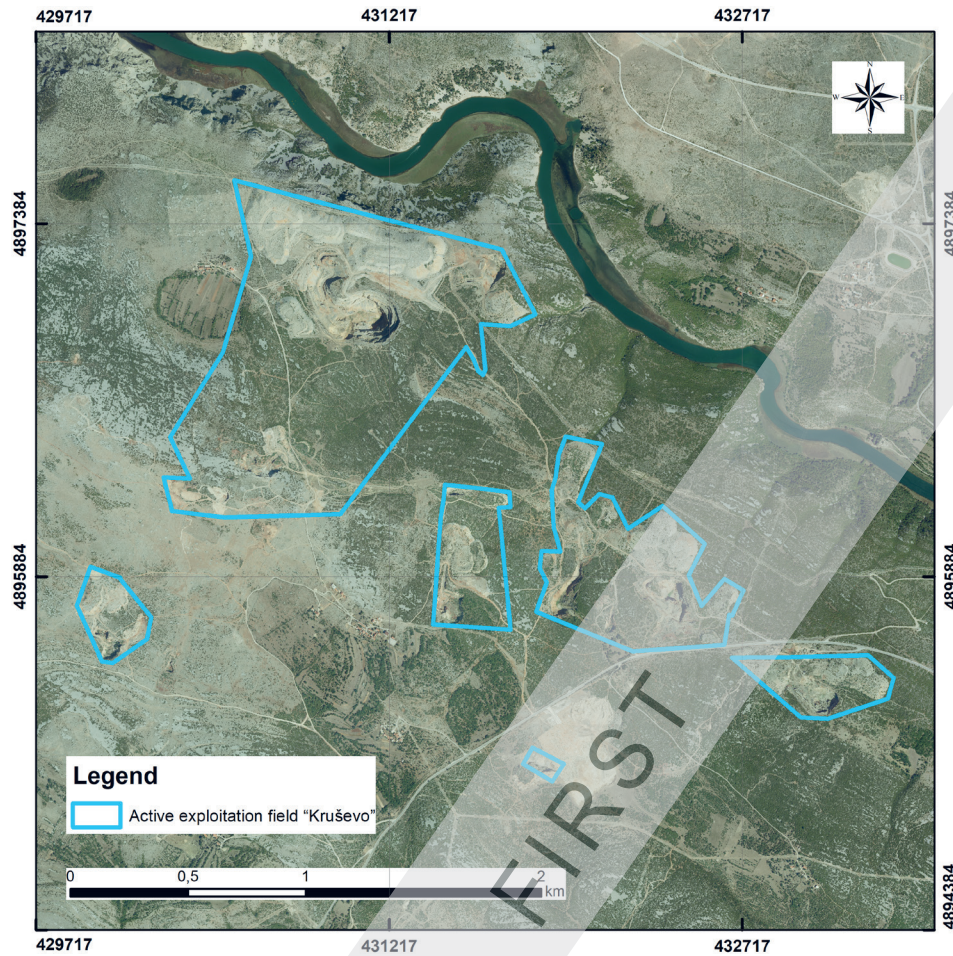


Figure 9. Spatial position of the active exploitation field with the valid concession “Kruševo” (EPSG:3765)

with core drilling, totalling 396 meters in length. Between 2018 and 2022, extraction was limited to crushed stone aggregates (Suppl. S1). In accordance with the UNFC system, the project would therefore be classified as a viable project, with the numerical codes E1 F1 G1, E1 F1 G2, or E1 F1 G3 (Fig. 10, Suppl. S2).

3.2.2. An active exploitation field with an invalid concession

The project timeline is critical for interpreting the following case and is discussed in detail in the Discussion section. A concession for the “Podevčevo” exploitation field was granted in June 2025 (Fig. 11, Suppl. S3); prior to that, mining had been conducted continuously since 1995, for approximately three decades. Following the introduction of the applicable Mining Act in 2013, operations continued under acquired rights, and the site remained active until the regulatory conditions for concession renewal were revised. The field is therefore classified as an active exploitation field with an invalid concession. The “Podevčevo” exploitation field was operated by Kamenolom Podevčevo d.o.o. with an invalid concession until mid-2025, and covers an area of 6.09 ha. After mid-2025, a concession was granted, regularising the operational status of the field. It is located in the north-western part of the Municipality of Novi Marof, on the eastern slopes of Mt Ivanščica, on the edge of the village of Podevčevo.

According to MIKO et al. (2025), the wider “Podevčevo” dolomite deposit is hosted within Middle Triassic carbonate and volcanic rocks. These units are exposed over an area of approximately 0.35 km² and are surrounded by Lower Miocene clastic deposits consisting of variably lithified sands, silts, clays, marls, and gravels, locally interbedded with tuffs. The contact between the Triassic and Miocene successions is either

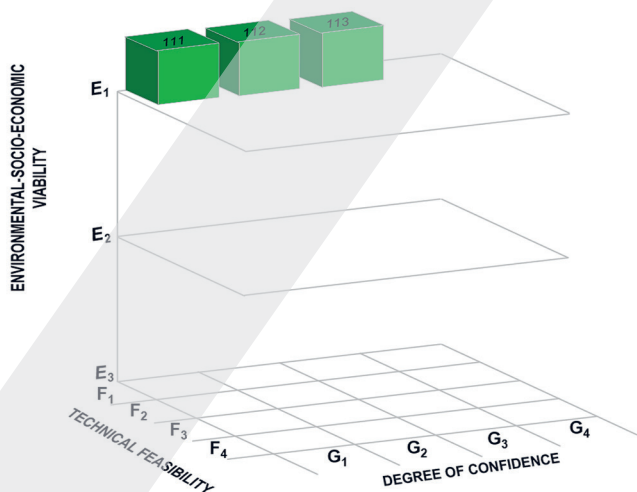


Figure 10. UNFC categories for the “Kruševo” active exploitation field with valid concession

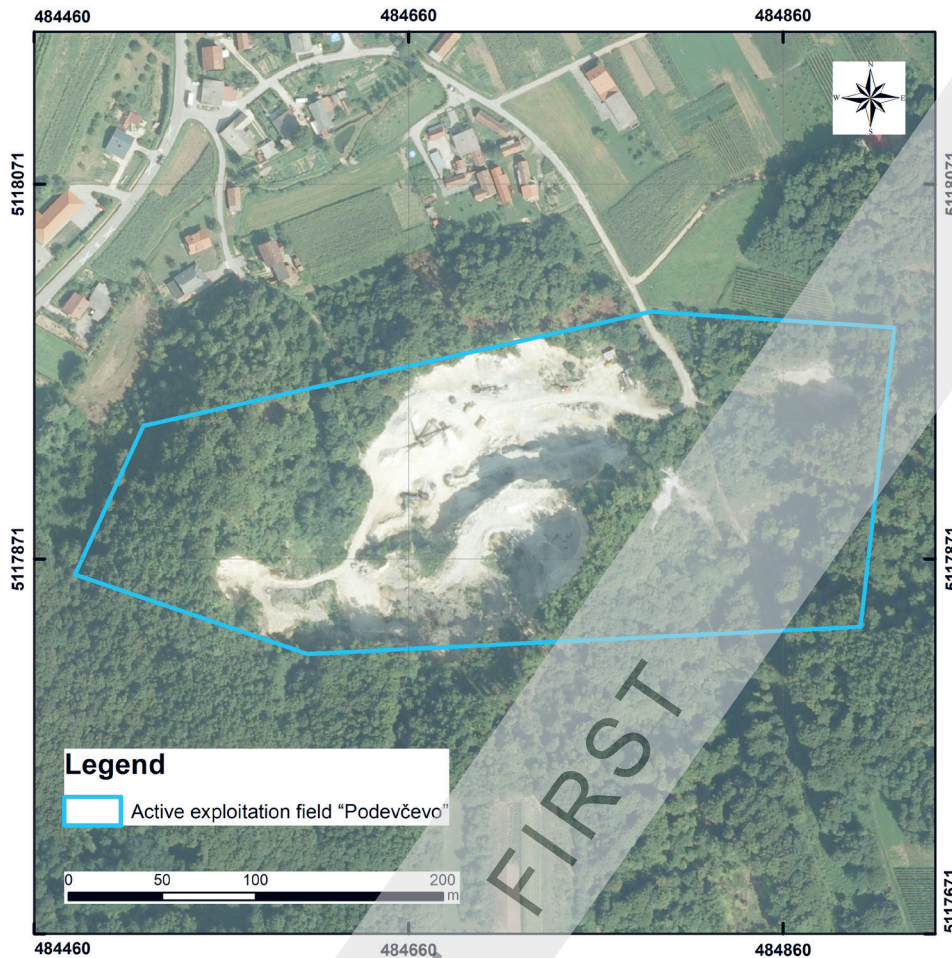


Figure 11. Spatial position of the active exploitation field with the invalid concession “Podevčevo” (EPSG:3765)

tectonic or transgressive. The Mt Ivanščica section is strongly tectonically deformed, as evidenced by variable bedding orientations in both successions and the presence of cataclastic breccias within the Triassic rocks, indicating multi-phase tectonic activity. The dolomite is greyish, largely massive, and commonly crushed. Given the historical mining activity, the quality of the rock mass at the existing quarry was assessed, yielding the following values: compressive strength: dry 163.4

MPa, water-saturated 164.2 MPa, and after freeze-thaw cycles 162.5 MPa; Boehme abrasion: 20.3 cm³/50 cm²; water absorption: 0.095 wt%; bulk density: 2.855 t/m³; porosity: 0.310 vol%; frost resistance: resistant.

In accordance with the UNFC system, the project would therefore be classified as a potentially viable project, with the numerical code E2 F2 G2, or even E3 F3 G2, depending on future activities (Fig. 12, Suppl. S4).

3.2.3. Non-active exploitation fields

The non-active bauxite exploitation fields of “Mamutovac” and “Krst Radas” (Fig. 13) were independently assessed by two qualified experts applying the UNFC criteria within their respective analytical frameworks. Both assessments were grounded in similar datasets, but the reviewers adopted slightly different analytical pathways, particularly in the interpretation of historical evidence, confidence levels, and the regulatory context. Despite these differences in approach, both assessments yielded equivalent UNFC outcomes. This convergence confirms that independent expert evaluation can produce consistent classification results when the UNFC framework is applied systematically.

3.2.3.1. The non-active exploitation field “Mamutovac”

The bauxite exploitation field “Mamutovac” is located in the north-western part of the Promina plateau. Within this

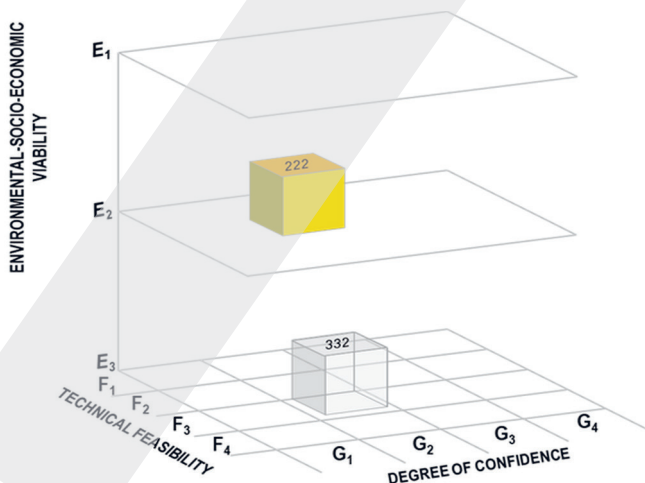


Figure 12. UNFC categories assigned to the active exploitation field “Podevčevo”

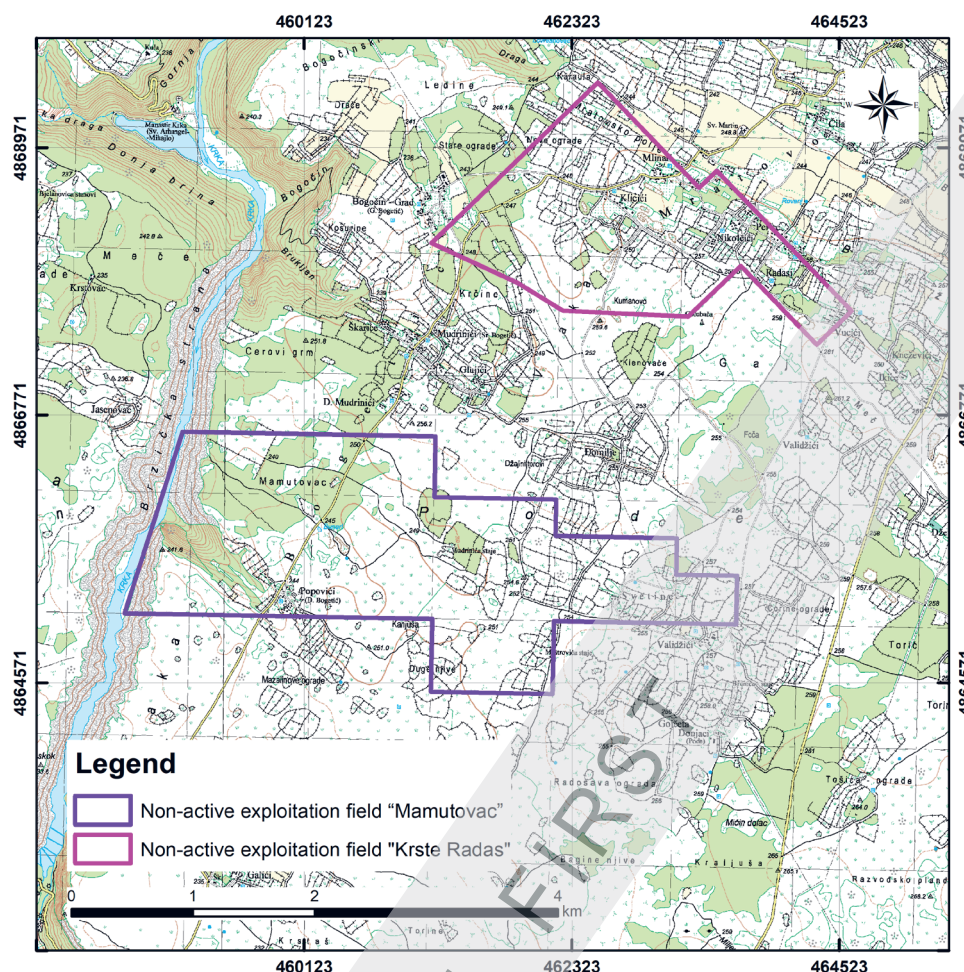


Figure 13. Non-active exploitation fields “Mamutovac” and “Krste Radas” (EPSG: 3765)

exploitation field, there were 10 bauxite deposits, including some depleted deposits. In the reserve report from 2004, 5 deposits (“Mamutovac Ia”, “Mamutovac II”, “Mamutovac III”, “Podi kod Uroša” and “Validžići”) were included in the exploitation field “Mamutovac”. All deposits are situated within an absolute elevation range of 244 to 256 metres. Upper Cretaceous rudist limestones or alveolina limestones of the lower Palaeogene underlie the bauxite deposits. Overlying the bauxite deposits are the heterogeneous Promina deposits, with conglomerates being the most common, followed by thinly layered marly limestones, and less frequently, marls. Promina deposits dip north-eastward at an angle of up to 45 degrees. The bauxites belong to the younger Palaeogene. The bauxite ore bodies have lengths and widths up to 100 metres and an average thickness of 4 metres, which corresponds to a medium-sized deposit in the context of Croatian bauxite deposits (KOVAČEVIĆ GALOVIĆ et al., 2025). They are often irregularly shaped lenses with uneven thickness and the morphology of the deposits can be quite variable. The contacts between bauxite and the underlying rocks are uneven due to the rugged palaeorelief. The bauxite is of böhmitic or mixed böhmitic-hydrargillitic composition. Its quality modulus is low, ranging from 2 to 4. Therefore, most of the bauxite in this exploitation field belongs, in terms of quality, to off-balance ore (KAVUR, 1970b; LUKŠIĆ et al., 2004).

The history of the project reflects the broader bauxite exploration efforts in the area. Activities began before the First World War, and exploitation started in 1915. However, the oldest systematized data on bauxite reserves in the “Mamutovac” exploitation field date back only to 1966. Extensive exploration works were conducted in 1955/56, 1962, and 1969/70. Outcrops of deposits were explored using trenches and shallow pits, while the extension of ore bodies beneath the cap was investigated by exploration drilling. Bauxite exploitation occurred on several occasions but on a limited scale. Additional exploration drilling was conducted in 1980/81. In order to confirm the quantity and quality of mineral reserves 100 boreholes were completed in 1983, 1988, 2004 and 2017. The first mining company to hold the exploitation rights was “Boksitni rudnici Drniš”, from 1960 to 1968, and the second and final was “Jadralski aluminij”, from 1968 to 2017 (KAVUR, 1970b). Mining stopped permanently in 2019. The most recent resource and reserve estimates available were published in 2004 under the national classification system (LUKŠIĆ et al., 2004). Three deposits from the exploitation field were explored separately, and the results of the exploration are displayed here as individual tables (Suppls. S5–S7). In this case, reserves are shown in tonnes (t) not in Mm^3 (million m^3), as in the previous tables, as per the standards of that time.

Using the UNFC framework, the bauxite exploitation field “Mamutovac” can be classified as a non-viable development

project, given that mining activities have been officially discontinued and no exploitation is currently planned. Consequently, the balance reserves are assigned to categories 322 and 323, which correspond to projects that are closed or historically abandoned. Furthermore, due to the limited quality of the bauxite (reflected in its poor quality modulus and classification as off-balance ore), the off-balance reserves are placed in categories 342 and 343, representing mineral quantities that have been geologically identified but are not considered for development at this time. This classification is consistent with the UNFC approach to legacy or depleted fields and provides a structured means of incorporating historical resource data into both national and international inventories. Evidence for each UNFC category is given in Supplementary Table S8, and Figure 14.

3.2.3.2. The non-active exploitation field “Krstes Radas”

The bauxite exploitation field “Krstes Radas”, covers 330.39 ha and is located in the southwest part of the Promina plateau, south and southeast of the village of Mratovo. At the time of the last estimation of the reserves, the exploitation field consisted of five to six bauxite deposits/ore bodies: “Mratovo”, “Lastve”, “Zrinski”, “Torići”, and “Krstes Radas”. The field also contained the “Kumanovo” deposit, which represents the sixth bauxite deposit, but the reserves in it have been depleted.

A minor part of the terrain is covered with cultivated Quaternary deposits. Road access exists to all deposits. All six deposits of this exploitation field are located along the contact planes deformed by two large synclines of the Promina area. The ore bodies rest on foraminiferal Eocene limestones, and are overlain by biocalcarenes and conglomerates of the Promina unit. The overlying layers have a relatively gentle dip of 25 to 30° towards the northeast. Other deposits belonging to this exploitation field are located in the “Kumanovo–Krstes Radas–Torići” syncline. Their underlying beds consist of rudist limestones, while the overlying ones belong to the Promina conglomerates. The overlying units are steeply inclined towards the axis of the syncline. No significant faults in these deposits have been identified, only short diagonal or

transverse fractures were observed. All ore bodies are irregularly shaped, and irregularly stratified.

The deposits of this exploitation field were explored and mined between the two World Wars. At that time, exploration was exclusively conducted through underground mining operations, preparing new parts of the mine. Two large underground facilities were developed: “Kumanovo” and “Krstes Radas”, where several hundred thousand tons of bauxite were mined using multiple-levels. Surface exposures of the nearby deposits of “Tomislav”, “Zrinski”, and “Fabijan” were also mined. These deposits were explored to depth through underground mining operations, albeit to a lesser extent because of their lower ore quality and bauxite concentration. In 1970, “Jadral” conducted exploration drilling from the “Fabijan” deposit to the “Zrinski” site, as well as at the “Lastve” and “Mratovo” deposits, which were expanded between 1973 and 1974 (KAVUR, 1970a). Data from the former “Boksitni rudnici Drniš” were used in calculating reserves and bauxite quality for the “Krstes Radas” underground facility, while reserves for other areas of the “Kumanovo” mine were written off, based on additional exploration drilling. The first mining company to hold ownership was “Boksitni rudnici Drniš”, from 1960 to 1968, and the second and final was “Jadral Jadranski aluminij”, from 1968 to 2017. Mining activity ceased in 1975.

The most recent resource and reserve estimates were published in 1974 using the national (ABC₁) classification system. Though all deposits in the field were explored individually, the results of the exploration are displayed in summary compilation tables (Suppl. S9). Based on the quality and exploitation conditions, the reserves in “Lastve” and “Zrinski” are registered as balance. In the “Mratovo” deposit, only the ore of higher quality is considered balance (economic), while the reserves in “Torići” and “Krstes Radas” deposits are off-balance. “Krstes Radas” bauxite reserves shown in Supplementary Table S9, are expressed in t (tonnes), as in the “Mamutovac” case.

Following the UNFC classification scheme, the balance reserves are assigned to categories 322 and 323 (Development Not Viable; closed, abandoned, historic), reflecting a closed and historically abandoned project without current development potential. The off-balance reserves are placed into categories 342 and 343 (Remaining products not developed from identified projects), indicating mineral quantities identified through previous exploration, but not currently considered viable for extraction (Fig. 14). This classification enables historical data from the bauxite exploitation field “Krstes Radas” to be integrated into modern resource inventories while acknowledging its legacy nature and development limitations. Evidence for each of the UNFC categories is given in Supplementary Table S10.

3.3. ABC₁ to UNFC bridging

The Croatian reserve classification system, structured through ABC₁ categories as prescribed in the relevant “Ordinance” and described earlier in the paper, reflects different levels of geological confidence in the reliability of the estimated quantities. For the purposes of applying the UNFC, categories

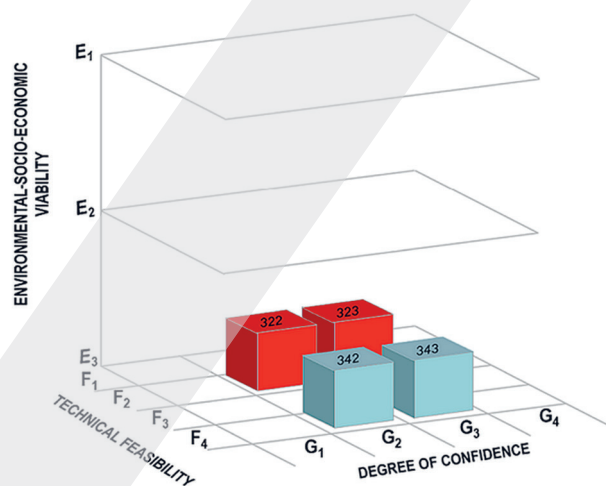


Figure 14. The non-active exploitation fields “Mamutovac” and “Krstes Radas” with their UNFC categories. The red categories correspond to “Mamutovac”, while the blue categories correspond to “Krstes Radas”

Table 4. Division of projects (exploration and exploitation) according to the Mining Authority as listed in the register of exploitation fields for mineral raw materials with bridging abbreviations used in Table 5.

No	Exploitation field	Bridging Abbreviation	Exploration area	Bridging Abbreviation
1	Active with valid concession	AEF	Active	AEA
2	Active with invalid concession	AEFIC		
3	Non-active	NAEF	Non-active	NAEA
4	Deleted	DEF	Deleted	DEA
5	Requested	REF	Requested	REA

A and B represent well-established balance reserves and correspond to G_1 , acknowledging the highest level of geological confidence. Category C_1 aligns with G_2 in brownfield settings, where previous exploration provides a moderate degree of geological confidence, or with G_3 in greenfield areas characterised by limited geological information. Category C_2 ,

which comprises potential but unconfirmed resources, is comparable to Potential Sources within the UNFC framework. All national off-balance reserve categories are assigned to Remaining products not developed from identified projects, consistent with their indicative nature but lack of feasibility. This mapping provides a consistent linkage between national reserve terminology and the UNFC project-based structure, forming the basis for the classification steps outlined in the following sections.

Table 4 summarises project categories defined in the applicable Croatian Mining Act (REPUBLIC OF CROATIA, 2023) and recorded in the national register of exploitation fields and exploration areas, with abbreviations added for UNFC mapping.

Building on this structure, Table 5 integrates these national project types into the UNFC classification scheme. Through a stepwise correspondence between project maturity

Table 5. Mapping from the national ABC_1 onto the UNFC classification system.

UNFC Classes defined by categories and sub-categories								
Produced	Sold or used production			INSPIRE Code List	Bridging abbreviation			
	Production which is unused or consumed in operations							
	Class	Sub-class	Categories			E	F	G
Total Products	Known Sources	On Production	1	1.1	1,2,3	operating continuously operating intermittently	AEF	
		Viable Projects	Approved for Development	1	1.2	1,2,3	under development	AEFIC REF
		Justified for Development	1	1.3	1,2,3	pending approval	AEFIC REF	
	Potentially Viable Projects	Development Pending	2	2.1	1,2,3	feasibility evaluation of the ore deposit	REF AEA	
		Development On Hold	2	2.1	1,2,3	care and maintenance retention	NAEF REF NAEA	
		Non-Viable Projects	Development Unclassified	3.2	2.2	1,2,3	resource assessment (geological interpretation, approximate calculation of the resource)	NAEA
	Development Not Viable	3.3	2.3	1,2,3	closed abandoned historic	DEF DEA		
	Remaining Products not developed from identified Projects	3.3	4	1,2,3			All categories of off-balanced	
	Prospective Projects		3.2	3.1	4	subsurface exploration		REA
			3.2	3.2	4	detailed surface exploration		REA
		3.2	3.3	4	regional reconnaissance		REA	
Potential Sources	Remaining Products not developed from Prospective Projects	3.3	4.1	4			Currently not applicable for Croatian solid mineral raw materials. Indicative character only. Depends on future technology development (e.g., tailings management).	
		3.3	4.2	4				
		3.3	4.3	4				

Table 6. A short version of the bridging form. The word “Active” refers to exploitation fields that are in operation, including those with valid and invalid concessions.

Project type	Status	National categories	National classes	UNFC E axis	UNFC F axis	UNFC G axis	UNFC class	UNFC sub-class	
Exploitation field	Active	Balance	A, B, C ₁	1	1	1, 2	Viable Project	On Production	
		Off-balance	A, B, C ₁	3	4	1, 2	Remaining Products		
	Non-active	Balance	A, B, C ₁	2	2	1, 2	Potentially Viable Project	Development On Hold	
		Off-balance	A, B, C ₁	3	4	1, 2	Remaining Products		
	Deleted	Balance	A, B, C ₁	3	2	1, 2	Non-Viable Project	Development Not Viable	
		Off-balance	A, B, C ₁	3	2	1, 2	Non-Viable Project	Development Not Viable	
	Requested	Balance	A, B, C ₁	1	1	1, 2	Viable Project	Justified For Development	
		Off-balance	A, B, C ₁	3	4	1, 2	Remaining Products		
	Exploration area	Active			2	2	1, 2, 3, 4	Potentially Viable Project	Development Pending
		Non-active			3	2	3, 4	Non-Viable Project	Development Unclassified
Deleted				3	2	3, 4	Non-Viable Project	Development Not Viable	
Requested				3	3	4	Prospective Projects		

(F-axis), environmental–socio-economic viability (E-axis), and geological confidence (G-axis), the table shows how each Croatian project category aligns with specific UNFC classes and sub-classes, from viable operating projects (e.g., AEF mapped to 1.1) to projects under development, projects on hold, non-viable or historic projects, and prospective projects associated with early-stage exploration. Together, these tables provide a bridging framework between national administrative categories and the UNFC project-based approach, ensuring that Croatian mineral data can be expressed in a consistent and internationally comparable manner.

The development of a methodology for translating from the national classification system to the UNFC system benefited from the use of Bridging Documents from countries with similar systems, the application of the UNFC Guidance Europe (UNECE, 2022), experience gained from EU projects and GSEU (2022–2027) training, the testing of case studies and national classifications, the incorporation of data analogies and experiences from other EU Member and neighbouring states, and the use of the UNFC template provided in the GSEU (2022–2027).

4. DISCUSSION

For legacy probability-based systems such as the ABC₁ classification system, the UNFC can serve as a corrective framework. While the ABC₁ system relies on the statistical estimation of quantities, the UNFC classification is grounded in the level of geological evidence and confidence available for each block. These dual perspectives provide the foundation for analysing the Southeast European experience. Countries of the former Yugoslavia (ex-YU) and Austria have approached the transition toward UNFC in different ways. Two distinct pathways emerge: a corrective pathway, characteristic of several former Yugoslav (ex-YU) countries where legacy ABC₁-type classifications require translation through formal or expert-based bridging approaches, and a proactive pathway exemplified by Austria, where reporting practices commonly follow the Committee for Mineral Reserves International Reporting Standards (CRIRSCO)-aligned Pan-European Reserves and

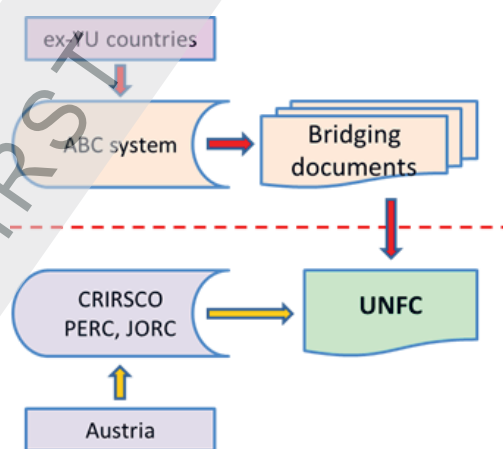


Figure 15. Former Yugoslavia (ex-YU) countries and Austrian pathways to UNFC classification

Resources Committee (PERC, 2021) standard, enabling direct alignment with the UNFC framework without the need for a dedicated national bridging document. Figure 15 illustrates these contrasting approaches, while Supplementary Table S11 summarises their key methodological features of a dual prospective approach. Hungary’s work illustrates how systematic bridging of long-standing national datasets to the UNFC can enhance the interpretability and long-term usability of mineral inventories, offering a practical model for countries facing similar legacy-system constraints (HORVÁTH, 2023; HORVÁTH et al., 2023).

4.1. EU Member states and neighbouring states experience

In Hungary, the transition toward the UNFC was developed by the Supervisory Authority for Regulatory Affairs (SARA) which oversees mineral resources and geothermal energy. The legal foundation is provided by the Mining Act (REPUBLIC OF HUNGARY, 1993): and the SARA (2022), which stipulate mandatory reporting procedures for companies. All in situ resources are state-owned, and companies are legally obliged to

provide annual updates on remaining resources and reserves to the state registers, while production data are reported through separate regulatory procedures. The national reporting framework is supported by two complementary databases. The Mineral Resource Inventory (MRI), established in 1953, documents geological reserves in categories A, B, C₁, and C₂. This inventory contains detailed geological, technical, and administrative attributes, including exploration data, quality indicators, mining methods, and reserve estimates. In addition, the Inventory of Mining Areas (BATER, Hungarian acronym) records the legal and operational status of mining plots and exploration areas, including approvals, suspensions, closures, and license details. For UNFC classification, Hungary applies a structured methodology. The G-axis is derived directly from geological knowledge stored in the MRI, while the E and F-axes are interpreted based on the project status as recorded in BATER and in Technical Operation Plans. For instance, an operating mine with a valid exploitation plan is classified as a Viable Project (E1.1, F1.1), a suspended mine as a Potentially Viable Project (E2, F2.2), and a mine without a valid license as a Non-Viable Project (E3.1, F2.3). This methodology has been tested using a series of case studies covering different commodities from non-metallic raw materials and metallic ores to hydrocarbons and geothermal sites. The Hungarian experience highlights both the strengths and limitations of the UNFC at a national level. A key strength lies in the legally binding reporting framework, which ensures annual updates and nearly complete data coverage. This mandatory system provides a high level of consistency in the inventories and creates an excellent basis for international harmonization. The dual-database design, separating geological knowledge (MRI) from project status (BATER), allows for efficient classification along the three UNFC axes and facilitates transparent communication with different stakeholders. Several challenges remain, as historical datasets need to be re-evaluated. Older exploration campaigns often lack the precision or documentation required to support direct mapping into the UNFC. In addition, information relevant to the E-axis may be scattered across multiple authorities, requiring significant institutional coordination. Finally, continuous updates of guidance are needed for the Hungarian system to evolve with the most recent UNFC specifications (e.g., UNFC Guidance Europe (UNECE, 2022)). For Croatia, which still applies the traditional ABC₁ classification system, the Hungarian example demonstrates that legal continuity can be preserved while the UNFC is gradually adopted as a parallel, internationally comparable framework.

In Slovenia, the introduction of the UNFC has been coordinated by the Geological Survey of Slovenia, which operates as the national authority for mineral resource management. The national system has traditionally followed the “Russian code” where categories A, B, and C₁ represent reserves with decreasing levels of geological confidence, while C₂, D₁, and D₂ refer to resources with more limited knowledge. Alongside geological certainty, the system also differentiates resources according to their economic potential, distinguishing between economic, potentially economic, and non-economic reserves. To bridge the Slovenian system to the UNFC, GeoZS developed a translation methodology that preserves the

continuity of geological knowledge while enabling alignment with the UNFC framework. A formal bridging document provides transparent equivalence between national ABC₁ categories and the UNFC numerical codes. Environmental and social considerations, including permit status, are considered within the project maturity assessments.

As a practical tool, a bridging document was prepared, providing clear equivalences between the national ABC₁ categories and the UNFC numerical codes. The methodological work has been supported by capacity-building activities. The UNFC was translated into Slovenian, and in 2024 a national document introducing the methodology and bridging rules was published. Concurrently, GeoZS organized workshops to train national experts, ensuring that the classification can be applied consistently across both industry and administration. Slovenia's approach demonstrates that a smaller country with a traditional classification system can successfully adopt the UNFC. The key strength lies in embedding the new methodology within existing legal and administrative structures, which provides continuity and minimizes disruption. By linking the national ABC₁ categories with the UNFC axes through a bridging document, Slovenia has created a transparent and reproducible system that allows its data to be compared with European and global inventories. However, some challenges remain. Current implementation focuses primarily on concession areas, while resources in exploration zones and undeveloped prospects are less systematically covered. Moreover, while regulatory clarity has been achieved, additional case studies across different commodities would further validate the robustness of the translation. Nevertheless, Slovenia has established itself as a positive example in the region. By combining methodological development, legal integration, and expert training, it has shown that the transition to the UNFC is both realistic and beneficial. Slovenian experience (ROKAVEC, 2024) highlights that historical datasets can be harmonised with only minimal disruption to existing practice, partly due to targeted capacity-building activities and systematic testing within national databases. For Croatia, the Slovenian experience highlights the benefits of early methodological preparation and shows that a structured bridging process can significantly enhance transparency, comparability and long-term integration into European resource-management frameworks.

In Serbia, the process of aligning national mineral resource classifications with international standards has been driven by both legislative reforms and professional initiatives. The Serbian system also relied on the historical ABC₁ categories, but over the past decade the country has gradually moved toward the utilization of CRIRSCO-aligned reporting codes, particularly the PERC (2021) and Joint Ore Reserves Committee (JORC, 2012) standards (ILICH & VUKAS, 2016; VUKAS, 2023, 2024). This shift provided a pathway for the adoption of the UNFC as a higher-level framework capable of bridging national and international practices. The Geological Survey of Serbia, in cooperation with universities and professional associations, has actively engaged in preparing bridging documents and testing the mapping of national categories to UNFC axes standards (ILICH & VUKAS, 2016;

VUKAS, 2023, 2024). Geological confidence (G-axis) is derived from the established ABC₁ framework, while economic viability (E-axis) and technical feasibility (F-axis) are assessed using project maturity and market conditions, as reflected in feasibility studies and licensing status. By structuring projects along these three axes, Serbian authorities ensured that their national resource inventory could be characterized in UNFC terms without abandoning the familiar national classification system (VUKAS, 2024). The Serbian example illustrates how a country with a traditional ABC₁ based classification can modernize its reporting system by first adopting CRIRSCO-aligned standards and then extending these to UNFC. This two-step pathway offers an effective transition model: CRIRSCO codes provide the technical rigor and competence requirements needed for credible reporting, while UNFC ensures comparability across resources and integration into broader policy frameworks. Strengths of the Serbian approach include the recognition of competent persons, the preparation of bridging documents, and the successful testing of UNFC categories on national projects. These elements provide confidence that Serbian data can be understood and compared internationally. Challenges remain in ensuring full consistency across all commodities, and in expanding the system from pilot projects to a full national inventory (ILICH & VUKAS, 2016; VUKAS, 2023, 2024). For Croatia, the Serbian experience is highly relevant. It demonstrates that even when a national system remains rooted in ABC₁ categories, international alignment is possible if bridging documents are prepared and if national institutions support the gradual adoption of UNFC. By following this approach, Croatia can preserve continuity with its legal framework while positioning its mineral resource data within the wider European and global reporting systems.

In Bosnia and Herzegovina, mineral resource management is shaped by a fragmented legal and institutional framework. Mining activities are regulated separately in the two entities, the Federation of Bosnia and Herzegovina and Republika Srpska, each with its own mining laws and concession policies (RENAUD, 2020). The Concessions Act from 2002 introduced procedures for granting mining rights, but it did not establish a harmonized classification system for mineral reserves and resources. As a result, no unified national inventory exists, and reporting practices differ significantly between the entities. Although Bosnia and Herzegovina has a long tradition of mineral exploitation, particularly in bauxite, coal, iron ore, and lead-zinc deposits, the classification of reserves remains inconsistent and is not directly linked to international reporting systems. To date, no bridging documents or methodologies have been developed to connect existing national practice to the UNFC framework. Moreover, institutional responsibilities are dispersed among multiple agencies, and there is no central geological survey coordinating a standardized national database. Recent reviews emphasize that the lack of systematic data collection and harmonized classification hinders integration with European initiatives such as the Geological Service for Europe (SANDIĆ, 2021; GSEU, 2022–2027). The Bosnian case highlights the challenges faced by countries with fragmented governance structures and limited institutional capacity for resource classification. While mining remains an

important economic sector, the lack of harmonized classification standards prevents reliable comparison with European neighbours. Furthermore, without bridging documents or methodological guidelines, Bosnia and Herzegovina is unable to position its resource base within either the UNFC or other international frameworks. For Croatia and other regional countries, this example underscores the importance of early institutional coordination and the development of bridging documents. The Bosnian experience suggests that without support from a central authority and a clear methodology, alignment with UNFC is unlikely to progress. In contrast, countries that have already invested in these steps, such as Slovenia, Hungary, and Serbia, are significantly better positioned to integrate into European mineral resource inventories.

Austria has approached the integration of the UNFC by embedding it directly into its geological and resource governance framework, without a legacy reliance on the “Russian code” system. The Austrian mining legislation (REPUBLIC OF AUSTRIA, 1999) regulates ownership, concessions, and exploration, while classification of resources is guided by international best practice, largely based on CRIRSCO-aligned reporting standards, rather than corrective translation of legacy national categories. Within this framework, Austria has adopted the UNFC as a strategic classification tool to ensure compatibility with European initiatives such as the Geological Service for Europe (GSEU, 2022–2027) and the European Geological Data Infrastructure (EGDI). The methodology is based on mapping national reporting standards – largely influenced by CRIRSCO templates (PERC, 2021; JORC, 2012) – directly into the UNFC’s three axes: economic viability (E), project feasibility (F), and geological knowledge (G). Instead, translation efforts focus on ensuring that feasibility studies and exploration reports are documented in a way that allows immediate coding into the UNFC categories. Capacity-building activities include training sessions, participation in UNECE expert groups, and the publication of methodological guidelines in collaboration with European partners. This proactive integration reflects Austria’s aim to align its geological service with both national resource policy and European raw materials strategies.

The Austrian case provides an important contrast to the experiences of countries in Southeast Europe. Austria aligned existing CRIRSCO-compliant reporting. The approach did not require translation of legacy classification systems, but instead focused on direct alignment and reclassification within internationally compatible reporting standards, emphasizing transparency and policy integration. A key strength of the Austrian model lies in its institutional centralization. With Geosphere Austria as the single geological authority, reporting and data management are streamlined, reducing fragmentation and ensuring consistency. The early integration of the UNFC into European collaborative projects ensured that Austria’s data were compatible at the continental level. Nevertheless, some challenges remain. Austria’s geological data for certain historical mining areas are incomplete or outdated, which complicates their translation into UNFC categories. Furthermore, while industrial minerals and geothermal projects have

been tested, a complete nationwide application of the UNFC across all commodities is still in progress. Austria demonstrates how UNFC can be embedded in a national system. For Croatia, this example illustrates that a forward-looking strategy, based on CRIRSCO standards, centralized data management, and alignment with European initiatives – can provide an efficient and policy-relevant pathway toward full UNFC integration.

The comparison between Southeast European (ex-YU) countries and Austria demonstrates two distinct pathways toward the adoption of UNFC. Countries of the former Yugoslavia, Slovenia, Serbia, and to some extent Bosnia and Herzegovina have had to manage the legacy of the ABC₁ system. Slovenia, for example, successfully developed a bridging methodology and integrated it into its Mining Registry Book (GeoZS, 2025), while Serbia relied on pilot projects and competent person reporting to achieve consistency. Bosnia and Herzegovina, however, has not yet moved beyond fragmented legal frameworks and has not produced results that could be assessed against UNFC standards (RENAUD, 2020; SANDIĆ, 2021).

Taken together, the regional comparison shows that while ex-YU countries have followed a corrective pathway; gradually replacing legacy classifications with internationally harmonized frameworks, Austria pursued a proactive strategy, embedding UNFC into governance and policy instruments from the outset. Both approaches demonstrate that UNFC can adapt to different national circumstances: as a bridging tool where legacy systems persist, or as a forward-looking framework where CRIRSCO standards already provide a solid foundation. For Croatia, this dual perspective offers valuable guidance: it can draw on the incremental experiences of its regional neighbours, while also learning from Austria's example of integration into European resource governance.

For Croatia, the experiences of the neighbouring and European countries provide both warnings and opportunities. Like much of Southeast Europe, Croatia relies on the ABC₁ system, meaning that any move toward UNFC will first still require the careful translation of legacy data. Yet, Croatia is in a more favourable position than Bosnia and Herzegovina, since its institutional framework is more unified and geological information is systematically managed. The Slovenian and Serbian cases show that bridging documents and pilot projects can offer a practical way forward, while Austria illustrates the advantages of embedding UNFC directly into resource governance and linking it with wider European strategies. Together, these examples suggest that Croatia's path will likely be a hybrid one: correcting and translating its ABC₁-based records, but at the same time adopting forward-looking practices that tie UNFC more closely to policy and European collaboration. By doing so, Croatia can not only modernise its national inventory but also ensure that its data are comparable, transparent, and relevant for both scientific use and policy-making.

4.2. Case study based discussion

The application of the UNFC to different types of exploitation fields in Croatia has proven highly effective for assessing the maturity and development potential of mineral exploitation

projects. The combined use of two complementary approaches, the ORAMA decision flow tools for active exploitation field with valid concession, and non-active exploitation field, and the direct application of UNFC guidance for active exploitation fields with a valid concession, active exploitation fields with invalid concessions, and non-active exploitation fields enabled a transparent and context-appropriate interpretation of the available evidence. This flexibility allowed the methodology to be aligned with the actual administrative, technical, and geological circumstances of each mining area. A particularly informative outcome emerged from the independent evaluations carried out for the "Mamutovac" and "Krste Radas" exploitation fields. Although the two experts assessed the same dataset, they applied different interpretative emphases and analytical pathways. Despite these methodological differences, both assessments ultimately converged on very similar UNFC categories. This demonstrates that, while expert judgement is an essential element of UNFC classification, the framework itself provides enough structure to ensure consistency and reproducibility. Minor variations in interpretation did not influence the overall classification outcomes, confirming the robustness of the system.

The "Podevčevo" exploitation field exhibits a clear geological potential for expansion. Surface exposures indicate possible enlargement by approximately 500% towards the south and east, with potential for additional resources deeper beneath a relatively thin Miocene overburden, particularly towards the southwest and north. To refine estimates and determine the nature of contacts controlling the overburden thickness, further investigations are necessary, including detailed geological mapping at 1:1,000 scale, geophysical surveys, and shallow core drilling. This project was initially classified as an active exploitation field with an invalid concession. The concession temporarily lapsed due to administrative circumstances, resulting in a period during which the operation lacked formally recognised extraction rights. In mid-2025, the concession was successfully re-established, restoring the project's status as an active exploitation field with the ability to operate and pursue potential expansion. This case demonstrates the value of the UNFC bridging approach. During the period of concession inactivity, the project could reasonably be assigned to UNFC category 222, or 332, reflecting regulatory uncertainty and limited exploration rights. Following concession reinstatement and the resumption of compliant operations, the project could transition to UNFC category 111, 112 or 113 only once full operational status was achieved. Figure 16 illustrates how changes in legal and operational status, rather than new geological information, can lead to reassignment within the UNFC classification framework. (Figs. 16, 17). The "Podevčevo" example therefore highlights how UNFC provides a transparent and flexible framework capable of capturing temporal changes in project status.

For fields that are requested, deleted, or otherwise defined solely by their administrative status, the direct application of UNFC guidance is sufficient. These cases highlight that the UNFC enables efficient reclassification in response to changes in specific non-geological elements, such as legal status,

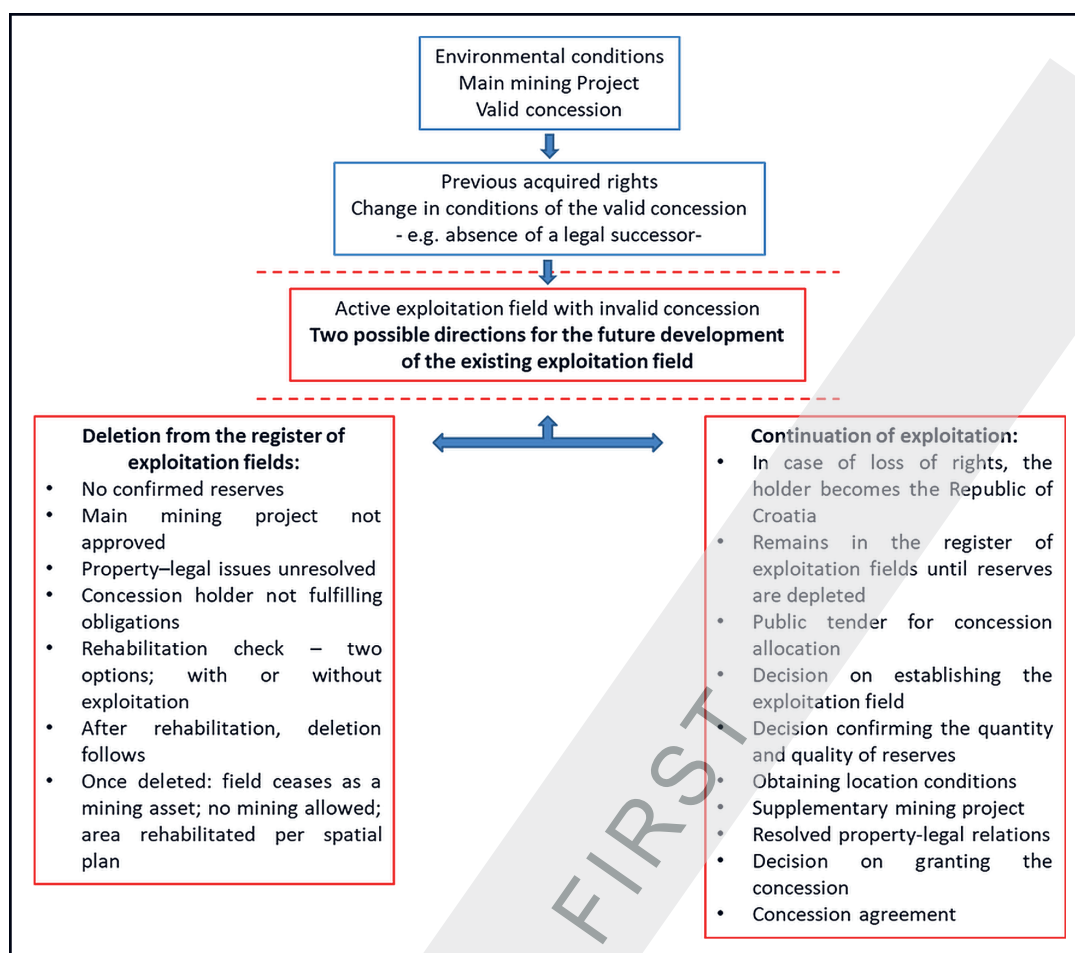


Figure 16. A short version of two possible directions for future development related to an active exploitation field with an invalid concession

operational activity, or permits, without requiring a full reassessment of geological evidence.

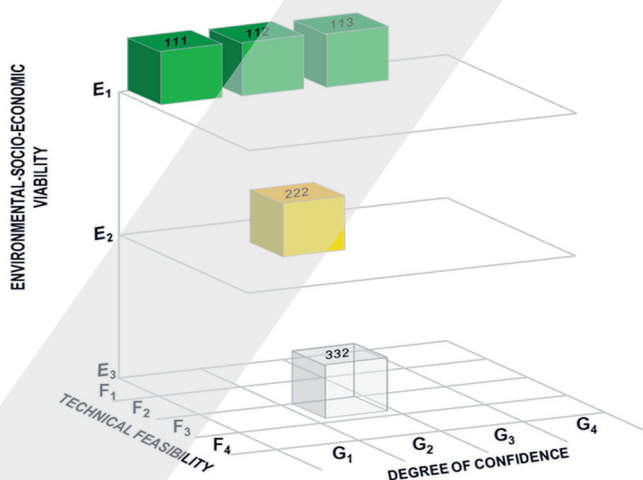
Uncertainties in UNFC mapping primarily arise from differences in data availability, exploration maturity, and the level of project documentation across case studies. These uncertainties mainly affect the assignment of F- and E-axis categories, while geological confidence (G-axis) is generally

better constrained. The adopted mapping approach therefore emphasises transparency and comparability rather than precise quantification.

5. CONCLUSION

The United Nations Framework Classification for Resources (UNFC) offers numerous benefits for resource management, exploration, and investment. It provides a standardized and transparent system, ensuring consistent reporting of resources that facilitates comparison and informed decision-making across regions and industries. Although the UNFC offers a clear and logical structure for resource classification, its application can be hindered by variations in data quality and differences in bridging with national reporting systems. These challenges can be mitigated by improved data standards, clearer guidance for integration with existing frameworks and targeted training for practitioners. Here, practices from neighbouring countries were reviewed and the adapted approach was subsequently tested on selected Croatian exploitation fields. Practices from Slovenia, Hungary, Bosnia and Herzegovina, and Serbia provided valuable context for evaluating the Croatian framework. Incorporating insights from the region therefore contributed to a balanced, well-integrated and contextually grounded interpretation of the UNFC within the Croatian setting.

Figure 17. The UNFC classification for the "Podevčevo" active exploitation field with an invalid concession. The green categories correspond to continuations of exploitation, while the yellow and white ones correspond to closure of the exploitation field



The test application of the UNFC framework to Croatian exploitation fields demonstrates that a structured and transparent classification system like the UNFC can be effectively

implemented across all solid mineral raw materials exploitation fields and exploration areas. Here, the focus was placed exclusively on solid mineral raw materials as defined by the applicable Mining Act, using representative examples from characteristic exploitation fields. Metallic mineral commodities, although included within the legal definition of solid minerals, are not currently exploited in the Republic of Croatia and are therefore referenced only within the broader classification context. The intention of this paper is not to encourage the replacement of the national system, but to demonstrate a transparent, functional, and reproducible pathway for applying the UNFC that strengthens its interoperability with existing national practices. Other resource groups within the scope of UNFC; such as hydrocarbons, geothermal energy, and anthropogenic resources, were not included, as their management lies within the remit of different national authorities. The methodological approach combining ORAMA decision flow tools for concessional aligned fields with the direct application of the UNFC guidance for inactive or administratively constrained sites, proved flexible and robust, enabling each field to be assessed according to its technical, geological, and regulatory characteristics.

The Table 5 Mapping from national ABC₁ to UNFC classification system is designed only for translating national classifications into the UNFC system, and not in the opposite direction. Many national (sub)classes do not align directly with individual UNFC sub-classes. Combining several national sub-classes is sometimes required to achieve an appropriate match.

The results confirm that the UNFC provides a coherent foundation for harmonising national resource reporting and contributes to the development of a unified European approach to responsible mineral resource management. Its capacity to integrate geological evidence, socio-economic viability, and regulatory status makes it a valuable tool for both current and future mining activities planning.

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Supplement S1–S11

Supplement S1. Active exploitation field “Kruševo” resources and reserves.

	Balance	Off-balance
Bauxite reserves (Mt)		
Proved	0.662128	1.139207
Probable	–	–
Carbonate mineral raw materials for industrial processing reserves (Mt)		
Proved	75.048143	34.353363
Probable	–	–
Crushed stone aggregates reserves (Mm ³)		
Proved	13.994370	6.837967
Probable	–	–

Supplement S2. Active exploitation field “Kruševo” bridging evidence for each of the UNFC Categories.

E-axis evidence	F-axis evidence	G-axis evidence
Mine is in production, therefore development and operation are confirmed to be environmentally-socially-economically viable.	Mine is in production therefore technical feasibility of a development project has been confirmed.	The archival material has been collected. Apart from several shorter periods caused by wartime events, the wider area of the exploitation field “Kruševo” has been systematically explored for about 90 years. The broader area of the existing exploitation field has been geologically mapped at scales of 1:100,000, 1:50,000, 1:25,000, 1:16,000, 1:10,000, and 1:1,000. The geological boundaries of bauxite in relation to other lithological units have been surveyed using geodetic methods. Surface and underground mining operations have been employed in the exploration. Particular bauxite occurrences have been further investigated through drilling. More than 100 chemical analyses have been conducted. Mineralogical and chemical examinations of characteristic bauxite species have been performed, which were later separated and analyzed individually.

Supplement S3. Active exploitation field with invalid concession “Podevčevo” resources and reserves (status as of May 2025).

	Balance (Mm ³)	Off-balance (Mm ³)
Crushed stone aggregates reserves		
Proved	0.695397	0.273333
Probable	–	–

Supplement S4. Active exploitation field with invalid concession “Podevčevo” bridging evidence for each of the UNFC Categories.

E axis evidence	F axis evidence	G axis evidence
Mine is temporarily not in production, but technically capable of resuming operations.	A Main Mining Project exists, however, an additional project will be required due to changes in technical conditions.	Archival documentation exists, reflecting the period when the exploitation field was in active operation and all required technical, geological, and regulatory materials were prepared accordingly. Geological mapping has been carried out at multiple scales (1:100,000; 1:50,000; 1:25,000; 1:16,000; 1:10,000; and 1:1,000). The geological boundaries of the dolomite in relation to surrounding lithologies were surveyed using geodetic methods. Hundreds of analyses have been performed.

Supplement S5. “Mamutovac la” bauxite reserves.

	Balance (t)	Off-balance (t)
Reserves:		
Proved	33,642	995
Probable	2,243	1,581

Supplement S6. "Mamutovac II" bauxite reserves.

	Balance (t)	Off-balance (t)
Reserves:		
Proved	–	–
Probable	13,252	5,742

Supplement S7. "Mamutovac III" bauxite reserves.

	Balance (t)	Off-balance (t)
Reserves:		
Proved	4,977	9,569
Probable	–	7,948

Supplement S8. The bauxite exploitation field "Mamutovac" bridging evidence for each of the UNFC Categories.

E axis evidence	F axis evidence	G axis evidence
Mine is no longer in production. The balance reserves are now 3 (or 3.3), as are the off-balance reserves.	Mine is no longer in production. The balance reserves are now 2 (or 2.3), while the off-balance reserves are 4 (Remaining products not developed from identified projects).	At the time of the creation of the last elaboration on reserves, the deposits were explored according to the current requirements and reserves were confirmed. Even though this was 50 years ago, the methods have not changed. A and B category of balance reserves would have been 1 on the G axis, while C ₁ would have been 2. Due to elapsed time, they are lowered to 2 and 3. A and B categories of off-balance reserves would also have been 1 on the G axis, while C ₁ would have been 2. Due to the elapsed time, they are lowered to 2 and 3.

Supplement S9. "Krstec Radas" bauxite reserves.

	Balance (t)	Off-balance (t)
Reserves:		
Proved	249,500	469,500
Probable	6,450	264,500

Supplement S10. The bauxite exploitation field "Krstec Radas" bridging evidence for each of the UNFC categories.

E axis evidence	F axis evidence	G axis evidence
Mine is no longer in production. The balance reserves are now 3 (or 3.3), as are the off-balance reserves.	Mine is no longer in production. The balance reserves are now 2 (or 2.3), while the off-balance reserves are 4 (Remaining products not developed from identified projects).	At the time of the creation of the last elaboration on reserves, the deposits were explored according to the current requirements and reserves were confirmed. Even though this was 50 years ago, the methods have not changed. A and B categories of balance reserves would have been 1 on the G axis, while C ₁ would have been 2. Due to the elapsed time, they are lowered to 2 and 3. A and B categories of off-balance reserves would also have been 1 on the G axis, while C ₁ would have been 2. Due to the elapsed time, they are lowered to 2 and 3.

Supplement S11. Key methodological features of a dual prospective approach.

Country	Starting Point	Methodological approach	Key Results / Status	Main Lessons for Croatia
Slovenia	ABC ₁ classification (A, B, C ₁ , C ₂)-	Bridging document developed by GeoZS; mapping ABC ₁ to UNFC axes; training and translation of UNFC, dual classification system.	Mining Registry Book integrated with UNFC codes; transparent online database.	Early preparation of bridging rules and stakeholder training ensures smooth transition.
Serbia	ABC ₁ classification, later PERC/CRIRSCO.	Gradual shift via PERC/JORC standards; pilot projects tested against UNFC.	Dual system: national classification + CRIRSCO reports mapped to UNFC.	Two-step transition (CRIRSCO → UNFC) provides technical credibility and comparability.
Bosnia and Herzegovina	Fragmented entity-based system, no unified classification.	No bridging documents or methodological guidelines. Focus on concessions and production data.	No results aligned with UNFC; lack of central geological authority.	Institutional fragmentation hinders progress; need for unified inventory and central coordination.
Austria	CRIRSCO-aligned PERC standard (no ABC ₁ legacy).	Direct integration of UNFC into Geosphere Austria workflows; alignment with EU projects.	Pilot projects (industrial minerals, geothermal) coded in UNFC; contribution to European guidelines.	Proactive strategy based on CRIRSCO aligned PERC standards and centralized governance ensures rapid integration.