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Rare Minerals in Carbonate Rocks as Indicators of Depositional Environment and Diagenetic Processes: A Literature Review

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ABSTRACTS

Rare or accessory minerals in carbonate rocks provide sensitive constraints on depositional environments and diagenetic pathways when interpreted within petrographic and geochemical context. This review synthesizes published case studies from marine platforms, mixed carbonate–evaporite systems, saline–alkaline lakes, and hydrothermal or fault-controlled settings to evaluate how uncommon mineral phases improve paleoenvironmental interpretation beyond conventional carbonate facies analysis. Minerals such as palygorskite, sepiolite, stevensite, high-Mg calcite, proto-dolomite, huntite, magnesite, glaucony, apatite/francolite, authigenic albite, fluorite, moganite, jarosite, and alunite are shown to form under restricted physicochemical conditions linked to fluid chemistry, redox state, evaporation, microbial mediation, meteoric flushing, or hydrothermal input. Mg-clays consistently indicate alkaline, Mg-rich lacustrine systems and early diagenetic cementation pathways, whereas Mg-carbonate phase assemblages record transitional stabilization histories of carbonate minerals. Evaporite replacement products, phosphate–glaucony associations, and low-pH sulphate minerals further constrain redox conditions and groundwater evolution. Authigenic albite and fluorite serve as tracers of hydrothermal or fracture-controlled fluids. The synthesis demonstrates that rare minerals are most diagnostic when integrated into paragenetic sequences and multi-proxy screening, enabling distinction between primary environmental signals and diagenetic overprints in carbonate archives.

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INTRODUCTION

Carbonate successions are widely used as archives of depositional conditions, yet their mineralogical and geochemical signals can be modified by post-depositional processes involving dissolution–reprecipitation and fluid–rock interaction in marine, meteoric, and burial settings (Gómez-Peral et al., 2007; Mueller et al., 2021). Consequently, many studies emphasize that the interpretability of carbonate-based proxies depends on assessing alteration using petrography and mineral-specific geochemistry (for example, cathodoluminescence, trace elements, and isotopes), rather than relying solely on bulk-rock data (Mueller et al., 2021; Ray, 2006). This caution is supported by evidence that some carbonate successions retain conservative isotopic or elemental signatures even after complex diagenetic or metamorphic overprints, whereas others experience substantial overprinting that can obscure primary environmental information (Mueller et al., 2021; Ray, 2006; Zhai et al., 2022).

Within this broader problem, rare or accessory minerals in carbonate rocks (for example, palygorskite, stevensite/sepiolite, glaucony, apatite/francolite, authigenic albite, fluorite, jarosite/alunite, moganite, and Mg-rich carbonate phases such as huntite or magnesite) have been repeatedly documented as sensitive indicators of (i) hydrological balance and alkalinity in lacustrine systems (Cupertino et al., 2023; Mocoroa et al., 2004; Sáez et al., 2003), (ii) restriction/evaporation and reflux in shallow-marine to marginal-marine platforms (Jiang et al., 2013; Zohdi et al., 2014), (iii) redox conditions in pore waters and bottom waters recorded by Fe-bearing authigenic phases and phosphate–glaucony associations (Algabri et al., 2020; Gómez-Peral et al., 2014), and (iv) hydrothermal or fault-controlled fluid circulation, reflected by mineral paragenesis and distinctive REE patterns or isotopic compositions (Chen et al., 2021; Herrero et al., 2011; Koeshidayatullah et al., 2020). Because these minerals often form under restricted physicochemical windows (for example, alkaline

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Mg-rich lake waters for Mg-clays (Cupertino et al., 2023; Sáez et al., 2003), low-pH oxidizing groundwater for jarosite/alunite cements (Potter-McIntyre & McCollom, 2018), or hydrothermal brines for saddle dolomite and associated phases (Chen et al., 2021; Koeshidayatullah et al., 2020), their presence can provide interpretive leverage beyond conventional carbonate facies descriptors (Nader et al., 2013; Vandeginste et al., 2013).

This review synthesizes published case studies spanning marine ramps and platforms, mixed carbonate–evaporite systems, saline–alkaline lakes, and hydrothermal/fault-related settings to evaluate how rare minerals in carbonate rocks constrain depositional environments and diagenetic pathways (Algabri et al., 2020; Bustillo et al., 2017; Cupertino et al., 2023; Gómez-Peral et al., 2007; Koeshidayatullah et al., 2020).

METHODS

Literature synthesis strategy

The review is based on a comparative synthesis of peer-reviewed case studies that (i) report accessory or uncommon mineral phases within carbonate rocks and (ii) explicitly link these phases to depositional conditions and/or diagenetic processes using petrographic and geochemical evidence (Algabri et al., 2020; Bustillo et al., 2017; Cupertino et al., 2023; Potter-McIntyre & McCollom, 2018). Emphasis is placed on studies integrating mineralogy with paragenetic interpretation through multi-method characterization, because such approaches are repeatedly argued to be necessary for distinguishing depositional from diagenetic signals in carbonate archives (Mueller et al., 2021; Ray, 2006; Zhai et al., 2022).

Analytical approaches emphasized in the reviewed literature

Across the reviewed studies, a recurring toolkit is used to identify rare minerals and place them into depositional–diagenetic context:

1. X-ray diffraction (XRD) to identify mineral phases (including Mg-carbonate polymorphs and Mg-clays) and quantify carbonate mineral chemistry/order (Bustillo et al., 2017; Cupertino et al., 2023; Elmagd & Matsumoto, 2022; Wen et al., 2020).
2. SEM/EDS and electron microprobe methods to resolve textures, zoning, and fine-scale mineral associations critical for paragenesis (for example, dolomite zoning, microbial-related fabrics, or replacement textures) (Koeshidayatullah et al., 2020; Y. Liu et al., 2022; Martire et al., 2014).
3. Cathodoluminescence (CL) to distinguish carbonate cement generations and recrystallization histories, commonly coupled to isotope/trace-element contrasts among phases (Ahmad et al., 2022; Chen et al., 2021; Nader et al., 2007).
4. Stable isotopes (C, O) and radiogenic Sr isotopes to infer fluid sources (seawater, meteoric water, mixed fluids, hydrothermal brines) and to evaluate diagenetic resetting risk (Jiang et al., 2013; Nader et al., 2008; Zhai et al., 2022; Zohdi et al., 2014).
5. REE + Y systematics as constraints on redox state, terrigenous contamination, and hydrothermal influence, including debate over preservation during diagenesis (Algabri et al., 2020; Bąk et al., 2016; Chen et al., 2021; Zhai et al., 2022).

This combination mirrors recommendations that reliable paleoenvironmental interpretations require phase-specific petrography and geochemistry to screen for alteration and to interpret mineral signals within a robust paragenetic sequence (Cui et al., 2017; Mueller et al., 2021; Ray, 2006).

RESULTS AND DISCUSSION

Conceptual Framework: Why Accessory Minerals can be Diagnostic

Several studies show that depositional facies can template early diagenesis and later fluid pathways, producing predictable spatial patterns in diagenetic minerals, including localized dolostone bodies, evaporite-related phases, or fracture-controlled cements (Nader et al., 2013; Vandeginste et al., 2013). At the same time, mineralogical stabilization in carbonates proceeds via dissolution–reprecipitation with different fluids (marine, meteoric, burial), systematically altering trace-element and isotopic compositions in ways that may be detectable through screening proxies (for example, Mn/Sr and $\delta^{18}O$ thresholds) (Gómez-Peral et al., 2007; Luo et al., 2024). Against this background, the occurrence of rare minerals is frequently interpreted as a “fingerprint” of the fluid chemistry, redox state, and/or saturation conditions during deposition or diagenesis—particularly where these minerals are restricted to specific facies or diagenetic zones (Algabri et al., 2020; Cupertino et al., 2023; Potter-McIntyre & McCollom, 2018).

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A key nuance is that some proxy systems may remain conservative despite diagenesis. For instance, seawater-like REY patterns (negative Ce anomalies and high Y/Ho) may be preserved in island carbonates even after meteoric diagenesis, marine burial diagenesis, or dolomitization (Zhai et al., 2022), and conservative marine $\delta^{13}C$–$\delta^{18}O$ values may persist under rock-buffered conditions during hydrothermal dolomitization or even contact metamorphism (Mueller et al., 2021). However, other work highlights that diagenesis can obliterate or strongly modify isotopic signals in carbonates, requiring component-specific screening and careful petrographic selection (Martín-García et al., 2009; Ray, 2006). Therefore, accessory minerals are most diagnostic when integrated with paragenesis and multi-proxy diagenetic screening, rather than treated as single-criterion indicators (Mueller et al., 2021; Ray, 2006; Zhai et al., 2022).

Mg-Rich Carbonate Phases (Proto-Dolomite, High-Mg Calcite, Huntite, Magnesite): Indicators of Fluid Chemistry and Diagenetic Stabilization

1. Proto-dolomite, ordering, and microbial/clay mediation in lacustrine systems.

Primary or near-primary microcrystalline dolomite is documented in evaporative lacustrine successions as laminated beds composed of nanoscale Ca–Mg carbonate crystals embedded in organic matrices and attached to clay flakes, interpreted to indicate strong evaporation and specific nucleation conditions (Wen et al., 2020). Microbial organotemplating is also documented in Miocene lacustrine dolomite–silica stromatolites, where extracellular polymeric substances (EPS) provide lattice-matching templates that facilitate dolomite nucleation and co-precipitation with silica, preserving microbial fabrics and yielding poorly ordered, non-stoichiometric dolomite (Sanz-Montero et al., 2008). These field observations align with experimental evidence that negatively charged clay minerals (for example, illite and montmorillonite) can facilitate abiotic proto-dolomite precipitation under ambient conditions by aiding cation binding/desolvation, whereas kaolinite is comparatively ineffective (D. Liu et al., 2019). Together, these studies support that proto-dolomite and poorly ordered Ca-rich dolomite in carbonates can indicate specific low-temperature nucleation pathways involving organic substrates and/or clay surfaces, rather than solely late burial replacement (D. Liu et al., 2019; Sanz-Montero et al., 2008; Wen et al., 2020).

2. High-Mg calcite and transitional Mg-carbonate phases in marine carbonates.

Rare preservation of high-Mg calcite (an unstable phase) in Triassic limestones has been documented and interpreted as early diagenetic in origin during compaction of shallow-marine deposits, potentially influenced by seawater conditions such as salinity and by Mg sourced from high-Mg skeletal components (Stanienda-Pilecki, 2018). Related Triassic studies identify multiple Mg-bearing carbonate phases—low-Mg calcite, high-Mg calcite, proto-dolomite, ordered dolomite, and huntite/de-huntite—based on XRD and microprobe constraints, emphasizing that carbonate successions can preserve a spectrum of transitional Mg-carbonate crystal structures rather than a simple calcite–dolomite binary (Stanienda-Pilecki, 2023; Stanienda-Pilecki & Jendruś, 2024). In environmental interpretation, these phase assemblages provide mineralogical evidence for early diagenetic pathways and subsequent stabilization histories that can be linked to evolving pore-water chemistry (Stanienda-Pilecki, 2018; Stanienda-Pilecki & Jendruś, 2024).

3. Magnesite and associated Mg-silicates as indicators of evaporitic restriction or hydrothermal alteration.

In Palaeoproterozoic successions, magnesite beds hosted by dolostones are interpreted to have formed by early diagenetic replacement of dolomite in playa/sabkha-like evaporitic environments, involving seawater-derived brines diluted by meteoric fluids, with later recrystallization during subsequent diagenesis/metamorphism (Melezhik et al., 2001). In contrast, Ediacaran Mg-rich carbonate successions in western Spain record magnesite and dolostone with minor talc, forsterite, and goethite, interpreted to reflect intense transformations associated with burial diagenesis and hydrothermal fluid circulation, superimposed on earlier peritidal deposition and evaporative dolomitization phases (Herrero et al., 2011). The contrast between evaporitic magnesitization models (Melezhik et al., 2001) and hydrothermal/burial transformation models (Herrero et al., 2011) illustrates that magnesite in carbonate rocks is not uniquely diagnostic of sabkha restriction; its interpretation depends on associated mineral assemblages (for example, Mg-silicates), textures, and broader basin/thermal context (Herrero et al., 2011; Melezhik et al., 2001).

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Mg-Clays in Carbonates (Palygorskite, Sepiolite, Stevensite/Kerolite): Proxies for Saline–Alkaline Lake Chemistry and Early Diagenesis

Accessory Mg-clay minerals in carbonate rocks are repeatedly tied to non-marine saline–alkaline conditions and to early diagenetic inhibition of “normal” carbonate cementation.

1. In lacustrine chalky carbonates of the Madrid Basin, palygorskite is reported as a common clay mineral forming coatings and sheets between carbonate crystals, and its early formation—combined with Mg-enriched pore fluids—was interpreted as a factor inhibiting calcite cementation, compaction, and recrystallization, preserving unusually high porosity despite deep burial (Mocoroa et al., 2004).
2. In the Green River Formation, multiple Mg-clay species (stevensite, mixed-layer kerolite–stevensite, and sepiolite) occur with calcite and dolomite in distinct Mg-clay-bearing lithofacies; these Mg-clays are explicitly described as valuable proxies for reconstructing shallow-water, saline–alkaline lacustrine palaeoenvironments because of their sensitivity to hydrochemical conditions (Cupertino et al., 2023).
3. Independently, a non-marine basin study documents that palygorskite and sepiolite can form as early diagenetic assemblages in shallow saline lakes and palustrine zones under Mg-rich alkaline waters, whereas other clay assemblages develop under more acidic conditions linked to organic matter accumulation (Sáez et al., 2003).

Synthesizing these findings, Mg-clays in carbonate rocks can serve as mineralogical evidence for alkaline, Mg-rich waters and restricted hydrology in lacustrine to palustrine settings, while also recording early diagenetic conditions that shape reservoir properties (for example, porosity preservation via cementation inhibition) (Cupertino et al., 2023; Mocoroa et al., 2004; Sáez et al., 2003). A key interpretive implication is that Mg-clay occurrence can be both environmental (lake chemistry) and diagenetic (early cementation pathways) in significance, requiring integration with facies and paragenesis (Cupertino et al., 2023; Mocoroa et al., 2004).

Evaporite-Related Rare Minerals and Replacement Products: Pathways Linking Restriction, Microbial Processes, and Meteoric Overprint

Mixed carbonate–evaporite systems generate distinctive rare-mineral assemblages through sequential replacement (gypsum/anhydrite ↔ carbonate ↔ silica) and later meteoric alteration.

1. In shallow lacustrine carbonate–evaporite deposits, dolostones commonly contain secondary calcite mimicking lenticular gypsum (pseudomorphs), alongside diverse dolomite crystal morphologies (tubes, cylinders, rhombs, spheroids), with dolomite tubes/cylinders interpreted as dolomitized microbial cells (Bustillo et al., 2017). The paragenesis is reconstructed as gypsum growth in calcareous mud followed by rapid dolomitization of muds, microbial communities, and gypsum, later vadose calcitization, and subsequent silicification linked to silica release during calcrete development (Bustillo et al., 2017).
2. In Eocene marine gypsiferous limestones, microbial sulphate reduction is inferred to drive carbonate replacement of evaporites (calcite, aragonite, dolomite), and this carbonate replacement in turn favors volume-for-volume silica replacement of carbonates; $\delta^{18}O$ signatures of quartz distinguish early marine/mixed fluids from later meteoric flushing (Henchiri & Slim-Shimi, 2006).
3. Early silicification in lagoonal carbonate–evaporite sequences further documents moganite as a transitional silica phase during conversion of opal-A or gypsum replacement, with organic matter and microbes playing a vital role in silica nucleation and preservation of early diagenetic textures (El-Hawat et al., 2020).

These studies converge on a process-based interpretation: evaporite minerals create strong chemical gradients (pH, Ca/Mg, SO_4 availability) that, together with microbial sulphate reduction and changing fluid sources, produce rare by-products (pseudomorphic calcite, microquartz/chalcedony/moganite, microbial dolomite morphologies) that encode both depositional restriction and diagenetic pathway dependence (Bustillo et al., 2017; El-Hawat et al., 2020; Henchiri & Slim-Shimi, 2006). The frequent involvement of microbial processes in evaporite replacement and mineral templating emphasizes that rare minerals may record coupled biogeochemical–diagenetic mechanisms rather than purely inorganic evaporation trends(Bustillo et al., 2017; El-Hawat et al., 2020; Henchiri & Slim-Shimi, 2006).

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Dedolomitization and Meteoric Diagenesis: Accessory Minerals and Fabrics as Indicators of Freshwater Incursion

Dedolomitization (calcitization of dolomite) is repeatedly linked to meteoric groundwater incursion in sulphate-bearing systems, producing distinctive fabrics that can be mistaken for other diagenetic pathways if paragenesis is not carefully reconstructed.

1. In mixed carbonate–evaporite successions, dedolomitization is interpreted to occur where dissolution of sulphate phases by undersaturated groundwater elevates Ca^{2+}/Mg^{2+} ratios, enabling replacement of dolomite by calcite; resulting fabrics include rhombic dedolomite textures that can form even without precursor dolomite rhombs, producing cloudy-core/clear-rim crystals (Hauck et al., 2018).
2. In Jurassic dolostones, sequential geochemical extraction and petrography support a major dedolomitization phase driven by karst-related meteoric waters carrying soil-derived carbon during uplift/emergence, with dedolomitization mechanisms strongly controlled by original dolostone texture (dissolution–precipitation versus mimic replacement) (Nader et al., 2008).
3. Complementary observations of selective dedolomitization in Upper Jurassic limestones (dolomite crystals partially replaced by calcite pseudomorphs) reinforce that dedolomitization can be localized and fabric-dependent, complicating environmental reconstructions if dolomite presence is assumed to be entirely depositional (Krajewski & Olchowy, 2021).

These findings imply that dedolomitization fabrics and associated mineralogical signatures provide indicators of meteoric flushing, karst hydrology, and sulphate dissolution in shallow burial settings, but only when interpreted in the context of precursor textures and evaporite association (Hauck et al., 2018; Krajewski & Olchowy, 2021; Nader et al., 2008). This directly supports broader cautions that carbonate mineralogy may record late-stage hydrological events rather than depositional environment alone (Martín-García et al., 2009; Ray, 2006).

Phosphate Minerals (Apatite/Francolite) and Glaucony: Indicators of Redox Conditions, Condensation, and Early Diagenetic Cycling

Accessory phosphate phases in carbonates and carbonate-associated phosphorites are repeatedly interpreted as redox- and productivity-sensitive archives, though their REE patterns may record significant diagenetic uptake.

1. A synthesis of Ediacaran–Cambrian phosphorites links phosphate accumulation to repeated condensation, early diagenetic and microbially mediated precipitation of carbonate-bearing francolite, and subsequent reworking; many samples show strong REE enrichment interpreted as post-depositional incorporation from anoxic pore waters following reductive dissolution of iron oxides, whereas preservation of primary seawater features (for example, Ce depletion, Y enrichment) is described as rare and mainly in shallow realms (Álvaro et al., 2015).
2. Phosphate–glaucony associations in the Ediacaran Doushantuo Formation are interpreted as recording generally suboxic early diagenetic environments with active exchange with bottom seawater, where Fe-redox cycling promotes phosphate and REE enrichment and extensive glaucony authigenesis; the association is proposed as a mineralogical proxy for paleoredox conditions on Precambrian seafloors (Algabri et al., 2020).
3. Cap-carbonate successions can contain well-developed apatitic cements associated with seafloor aragonite fans; a model ties phosphogenesis to an oxic–anoxic boundary near the sediment–water interface, “iron pumping,” and Fe^{2+} inhibition of carbonate nucleation, emphasizing that accessory apatite can encode coupled redox stratification and early diagenetic nutrient cycling (Okubo et al., 2018).
4. In Neoproterozoic successions, phosphogenic events and phosphate concretions/breccias are explicitly investigated using major/trace/REE data and isotopes, with discussion that positive Eu anomalies are uncommon in marine sediments but can reflect specific oceanographic or chemical-sediment conditions (Gómez-Peral et al., 2014).
5. Across the Precambrian–Cambrian transition, carbonatic phosphorites preserve radiogenic Sr, stable isotopes, and elemental (including REE) records interpreted as near-primary based on microstructural and trace-element screening, illustrating that some phosphatic–carbonate systems can retain interpretable environmental signals despite diagenetic risk (Stammeier et al., 2019).

Taken together, apatite/francolite and glaucony in carbonate settings most consistently indicate early diagenetic processes operating under suboxic to anoxic pore-water regimes with Fe-redox cycling and low sedimentation/condensation contexts, rather than simple “high productivity” deposition alone (Algabri et al., 2020; Álvaro et al., 2015; Okubo et al., 2018). However, the same literature emphasizes that REE enrichments in phosphorites frequently reflect post-depositional scavenging from pore waters,

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so mineral presence and REE patterns must be interpreted with explicit attention to diagenetic uptake pathways (Algabri et al., 2020; Álvaro et al., 2015; Gómez-Peral et al., 2014).

Authigenic Silicates and "Exotic" Cements in Carbonates: Albite, Fluorite, and Hydrothermal Indicators

1. Authigenic albite in limestones.

Euhedral, chemically pure authigenic albite occurs in Jurassic limestones with high carbonate content, and its formation is discussed in relation to diagenetic versus hydrothermal origins, with clay mineral transformation proposed as an important ion source; its restricted distribution highlights strong host-rock controls on authigenesis (Rais et al., 2007). In a lacustrine rift-basin setting with hydrothermal activity, hydrothermal-sedimentary dolostones contain coexisting hydrothermal minerals including albite, analcime, buddingtonite, and chalcedony; replacement of albite clasts by dolomite is used as evidence of elevated-temperature conditions during syn-depositional formation (Zhang et al., 2020). The combined message is that authigenic albite (whether in marine limestones or hydrothermal lake dolostones) can indicate specific diagenetic/hydrothermal geochemical regimes and host-rock compositional thresholds, rather than being a ubiquitous burial product (Rais et al., 2007; Zhang et al., 2020).

2. Fluorite as a hydrothermal tracer in dolostone reservoirs.

In shallow-burial dolostone reservoirs, late diagenetic hydrothermal fluids can be identified by authigenic fluorite filling fractures, distinguishing late hydrothermal events from earlier reflux dolomitization and meteoric dissolution/cementation stages (Lan et al., 2023). This aligns with broader frameworks in which fault- or fracture-controlled fluid flow can introduce distinctive mineral phases that overprint earlier diagenetic fabrics, requiring paragenetic sequencing to avoid misattribution to depositional settings (Nader et al., 2007; Vandeginste et al., 2013).

Low-pH Minerals (Jarosite and Alunite Group): Indicators of Oxidizing Acidic Diagenesis and Groundwater-Table Dynamics

Jarosite and alunite group minerals are described as precipitating at low pH in oxidizing environments and occurring as diagenetic cements in Jurassic sandstones deposited in marginal marine to coastal settings; their paragenesis is linked to fluctuating groundwater tables and ferrolysis that drove groundwater acidification, with microbial interaction suggested to contribute to acidity evolution (Potter-McIntyre & McCollom, 2018). While this case is sandstone-hosted, it provides a process-based analogue directly relevant to carbonate successions because carbonate-associated environments with fluctuating water tables and oxidation fronts can similarly experience localized acidic diagenesis; the key mineralogical inference is that jarosite/alunite presence signals episodes of oxidizing, acidic pore waters inconsistent with neutral marine carbonate precipitation (Potter-McIntyre & McCollom, 2018). Therefore, when such low-pH minerals occur in carbonate-hosted systems or carbonate-adjacent diagenetic zones, they can be interpreted as markers of unusual diagenetic conditions (acidic oxidizing) that strongly constrain groundwater chemistry and redox state (Potter-McIntyre & McCollom, 2018).

Implications for Proxy Preservation: Reconciling Conservative Versus Overprinted Signals

A persistent theme in carbonate archive research is that diagenesis does not have a uniform effect on mineralogical and geochemical proxies. Studies of limestone-to-marble transects argue that, under rock-buffered conditions, $\delta^{13}C$ and $\delta^{18}O$ values can remain conservative even through hydrothermal dolomitization and metamorphism, implying that mineralogical alteration does not automatically equate to proxy resetting (Mueller et al., 2021). Similarly, island carbonates can retain seawater-like REY patterns regardless of meteoric diagenesis, marine burial diagenesis, or dolomitization, suggesting robust preservation of certain REY characteristics (Zhai et al., 2022). By contrast, Sr isotope stratigraphy and other proxy applications explicitly caution that many dolostones and altered carbonates yield radiogenic or modified values indicative of heavy diagenetic alteration, motivating component-specific sampling and screening (Ray, 2006), and speleothem studies show that meteoric diagenesis (micritization, neomorphism, inversion) can modify stable isotopes and trace-element contents, potentially erasing primary textures and signals (Martín-García et al., 2009). These partially divergent conclusions underscore that accessory minerals should be interpreted within a framework that (i) reconstructs paragenesis, (ii) evaluates openness of the diagenetic system and fluid composition, and (iii) uses mineral-specific screening metrics rather than assuming either universal

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preservation or universal resetting (Martín-García et al., 2009; Mueller et al., 2021; Ray, 2006; Zhai et al., 2022).

CONCLUSION

The reviewed literature demonstrates that rare or accessory minerals in carbonate rocks can serve as powerful indicators of depositional environment and diagenetic processes when interpreted within petrographic and geochemical context. Mg-clays (palygorskite, stevensite, sepiolite) consistently point to saline–alkaline lacustrine to palustrine systems and can record early diagenetic controls on compaction and cementation. Mg-rich carbonate phase assemblages (high-Mg calcite, proto-dolomite, huntite/de-huntite) provide mineralogical evidence for early diagenetic pathways and stabilization histories, while magnesite may indicate either evaporitic sabkha/playa brines or hydrothermal/burial alteration depending on associated minerals and textures. In mixed carbonate–evaporite settings, rare mineral by-products (gypsum pseudomorph calcite, microbial dolomite morphologies, moganite/chalcedony) encode process pathways involving evaporation, microbial sulphate reduction, and later meteoric flushing. Phosphate minerals and glaucony provide mineralogical constraints on suboxic early diagenetic conditions driven by Fe-redox cycling and condensation/upwelling contexts, but their REE signatures commonly reflect diagenetic uptake from pore waters. Finally, authigenic albite, fluorite, and low-pH minerals (jarosite/alunite) offer particularly diagnostic constraints on hydrothermal inputs, fracture-controlled late fluids, or acidic oxidizing diagenesis—conditions that strongly shape carbonate diagenetic evolution even when depositional facies remain similar.

A central synthesis is that rare minerals are most informative when integrated into paragenetic sequences and combined with multi-proxy screening, because diagenetic alteration can sometimes preserve conservative environmental signals and sometimes severely overprint them. Accordingly, future carbonate paleoenvironmental reconstructions and diagenetic models can be strengthened by routine documentation of accessory mineral assemblages and their microtextural relationships, alongside phase-specific geochemical analysis rather than bulk-only approaches.

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