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Nanoscience and Nanotechnology in Geosciences: A Multiscale Framework from Mineral Interfaces to Earth-System Applications

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Abstract
This critical review develops a multiscale framework for nanoscience and nanotechnology in geosciences, linking atomic- and nanoscale processes to observable behavior in rocks, soils, sediments, aquifers, reservoirs, ore systems, and engineered subsurface environments. The central argument is that nanoscale phenomena are not peripheral to geology: surface energy, interfacial charge, non-classical nucleation, colloid transport, redox reactions, adsorption, dissolution-precipitation, and nanoconfined fluids can govern macroscopic transport, mechanical response, resource recovery, and environmental risk. The review distinguishes natural, incidental, and engineered nanomaterials; evaluates modern characterization strategies; and synthesizes applications in clay science, environmental geochemistry, hydrogeology, mineral exploration, petroleum systems, geotechnical engineering, atmospheric and soil processes, geothermal systems, carbon storage, and emerging subsurface energy technologies. Particular attention is given to the gap between laboratory reactivity and field-scale performance, where aggregation, pore-throat filtering, mineralogical heterogeneity, salinity, natural organic matter, pressure-temperature conditions, and residence time can reverse conclusions drawn from simplified experiments. A risk-aware perspective is adopted for engineered nanomaterials, emphasizing transformation, exposure, reversibility, and standardized reporting. The review concludes that the next stage of nanogeoscience will depend less on demonstrating isolated nanoscale effects and more on quantitatively connecting them to field observables through correlative characterization, reactive-transport modeling, uncertainty analysis, and carefully designed field validation.

Keywords
Nanogeoscience, Nanominerals, Mineral nanoparticles, Mineral-fluid interfaces, Colloids, Nanoremediation

1. Introduction

Geosciences are increasingly expected to support secure water supplies, critical-mineral production, low-carbon energy systems, resilient infrastructure, and environmental protection at the same time (Hinsby et al., 2024; Silva et al., 2025; Akhtar et al., 2026). These demands expose a limitation of explanations based only on bulk mineral composition, grain size, porosity, or regional geological

setting: many rate-controlling reactions occur at interfaces whose characteristic dimensions are nanometric. Iron oxyhydroxide particles can scavenge trace metals, clay edges can regulate ion exchange, nanometre-scale pores can impose confinement on fluids, and colloids can transport otherwise sparingly soluble elements. The recognition of these mechanisms has transformed nanoscience from a specialized analytical niche into a conceptual component of Earth-system science (Hochella et al., 2008; Banfield and Zhang, 2001; Gilbert and Banfield, 2005; Alivisatos, 2016; Shi et al., 2024; Kumar et al., 2025).

Natural nanoparticles are generated continuously by weathering, precipitation, hydrothermal reactions, volcanic activity, biological processes, and mineral transformation. Incidental nanoparticles arise from combustion, mining, grinding, industrial processing, and other anthropogenic activities, whereas engineered nanomaterials are intentionally designed for functions such as contaminant reduction, adsorption, catalysis, wettability alteration, or stabilization (Goswami et al., 2017; Barhoum et al., 2022; Mota et al., 2025). These categories may converge after release because coatings, aggregation, dissolution, sulfidation, oxidation, and mineral attachment can rapidly change particle identity. Consequently, the environmentally relevant object is often not the pristine particle but the transformed particle-mineral-organic assemblage that exists under actual geological conditions (Hochella et al., 2019; Lowry et al., 2012; Lespes et al., 2020).

A central challenge in nanogeoscience is therefore not simply to identify nanoscale features, but to determine when and how they influence processes at larger geological scales. High surface-area-to-volume ratios, surface charge heterogeneity, confinement effects, and short transport distances can make nanoparticles and nanopores disproportionately reactive relative to their abundance (Wang, 2014; Guan and Liu, 2026). However, nanoscale behavior cannot automatically be extrapolated to natural systems, where mineral heterogeneity, pore-network connectivity, fluid chemistry, organic matter, redox gradients, and hydrodynamic conditions may amplify, suppress, or redirect these effects.

Fig. 1. Multiscale framework of nanoscience and nanotechnology in geosciences, linking nanoscale processes to Earth-system applications (compiled from Banfield and Zhang, 2001; Gilbert and Banfield, 2005; Hochella et al., 2008; Hochella et al., 2019)

Establishing meaningful links from molecular and interfacial mechanisms to pore-, core-, reservoir- and field-scale responses is consequently essential for translating nanoscience into geoscientific understanding and practical decision-making (Johnson, 2020; Zhang et al., 2024; Chogani et al., 2025). This multiscale perspective also provides a basis for distinguishing mechanistically important nanoscale controls from observations that are analytically interesting but have limited consequences under realistic geological conditions. Existing literature on nanogeoscience is extensive but remains highly fragmented across disciplinary and application-specific boundaries.

Nanomineralogy, clay surface chemistry, environmental nanoremediation, enhanced oil recovery, soil nanoparticles, mineral–fluid interactions, and advanced nanoscale characterization are commonly treated as separate research domains, often with limited integration of their underlying mechanisms. Such compartmentalization can obscure the fact that many apparently distinct geological problems are governed by a common set of nanoscale processes (Hochella, 2008; Wang, 2014; Jun et al., 2016; Ju et al., 2017; Dorn et al., 2021).

A geological synthesis therefore requires a different organizing principle: rather than classifying studies primarily by application, it should identify the transferable interfacial mechanisms, such as adsorption, dissolution–precipitation, surface complexation, wettability alteration, aggregation, nanoconfinement, and colloidal transport, that recur across apparently unrelated geological settings (Li et al., 2021; Pham et al., 2024; Tong et al., 2024; Wu et al., 2024; Li et al., 2025; Zhu et al., 2026).

Adsorption matters in both contaminated aquifers and geochemistry; wettability governs hydrocarbon recovery and geologic CO_2 behavior; nanoconfinement affects clay barriers and reservoir fluids; and nucleation links mineral scaling, weathering, and hydrothermal deposition (Javanbakht and Levitas, 2018; Johnson, 2020). This review therefore treats nanoscale mechanisms as transferable process concepts and evaluates how they scale into field behavior. Its objective is to provide a unified, critical framework rather than an inventory of nanotechnology applications. The integrated conceptual architecture used in this review is summarized in Fig. 1.

1.1. Review Scope and Evidence Selection

This article is a critical narrative review rather than a formal systematic review or meta-analysis. Evidence was selected to represent foundational concepts, authoritative books and standards, well-established process studies, and recent developments that materially change interpretation in geoscience applications.

Evidence is evaluated at three levels. The first is mechanistic credibility: whether an observation identifies a physically or chemically plausible nanoscale process. The second is matrix relevance: whether the process persists in realistic minerals, waters, brines, pressures, temperatures, and pore structures. The third is scale relevance: whether the effect can be linked to measurable transport, reaction, mechanical, or operational behavior beyond the microscopic sample. This hierarchy is used throughout the review to distinguish mature geological insight from promising but still laboratory-bound nanotechnology (Bourg and Ajo-Franklin, 2017; Ngoma and Kolawole, 2024).

Table 1. Operational classification of nanoscale materials in geosciences (synthesized from Hochella et al., 2019; Lespes et al., 2020; Lowry et al., 2012; ISO, 2023)

Class	Typical origin	Geoscience examples	Primary interpretive issue
Natural	Weathering, precipitation, hydrothermal or biological processes	Ferrihydrite, clay nanoparticles, carbonate nanophases, natural colloids	Distinguish stable mineral populations from transient reactive phases
Incidental	Combustion, mining, grinding, metallurgy, transport and industrial processing	Ultrafine mineral dust, metal-rich ash, process-derived particles	Source apportionment and transformation after release
Engineered	Purposeful synthesis for defined functions	nZVI, silica nanofluids, nano-oxides, nanoclays	Transport, performance, persistence, reversibility and risk

Studies were excluded from the evidentiary core when the bibliographic record was internally inconsistent, when the subject was only tangentially related to nanoscale geoscience, or when application claims could not be traced to a defined geological mechanism. Foundational older papers were retained where they introduced concepts that remain necessary for interpreting newer results, while recent studies were used selectively to update areas in which analytical capability or field interpretation has changed.

This balance is important in a review of nanogeoscience because rapidly increasing publication volume can otherwise obscure the distinction between durable process knowledge and short-lived application trends.

1.2. Process-based Framework and Cross-scale Integration

The organizing framework of this review is process-based rather than application-based. Instead of treating groundwater remediation, mineral resources, geoenergy, soils, and engineered geological systems as independent domains, the review focuses on a common set of nanoscale processes that operate across these environments. These include surface complexation and adsorption, ion exchange, dissolution and precipitation, redox transformation, nucleation, aggregation and dispersion, wettability alteration, nanoconfinement, and colloid-mediated transport. Their relative importance varies with mineralogy, fluid composition, pH, ionic strength, temperature, pressure, pore geometry, and organic matter, but the underlying interfacial principles are transferable across geological settings.

A central challenge is that nanoscale observations do not automatically translate into field-scale significance. High surface reactivity or strong adsorption measured for isolated nanoparticles, for example, may be substantially modified by aggregation, surface passivation, competitive sorption, mineral attachment, or restricted transport in natural porous media. Conversely, processes occurring over only nanometres can exert macroscopic control when they are concentrated at reactive interfaces, repeated throughout extensive pore networks, or coupled to fluid flow and mineral transformation. The relevant question is therefore not simply whether a nanoscale effect exists, but under which geological conditions it persists, propagates across scales, and becomes measurable at the continuum or field scale.

Accordingly, the synthesis follows a cross-scale sequence from nanoscale structure and interfacial properties to particle- and surface-scale reactions, pore-scale transport and transformation, continuum-scale behavior, and ultimately field-scale performance and environmental implications. This structure provides a common basis for comparing evidence from different branches of geoscience and for identifying where mechanistic understanding is sufficiently mature for prediction, where scale-up remains uncertain, and where future analytical, experimental, and modeling efforts should be concentrated.

2. Scope, Terminology and Multiscale Problem

The widely used 1–100 nm interval is an operational convention rather than a geologically absolute boundary. A mineral or geological material may exhibit nanoscale behavior because of particle size, pore dimensions, interfacial films, surface domains, crystal defects, or reaction fronts even when the host grain is substantially larger. In such cases, nanoscale dimensions can alter surface energy, chemical potential, adsorption capacity, dissolution and precipitation kinetics, redox behavior, fluid organization, and transport pathways. For this reason, nanogeoscience is most useful when it refers not simply to materials that satisfy a prescribed size criterion, but to processes whose mechanism, rate, or consequence depends materially on nanoscale structure or confinement. ISO vocabulary provides an important basis for standardizing terminology, but geological interpretation still requires process-based judgement because natural particles are commonly polydisperse, aggregated, compositionally heterogeneous, structurally defective, and coated by organic or inorganic phases (ISO, 2023; Hochella et al., 2019).

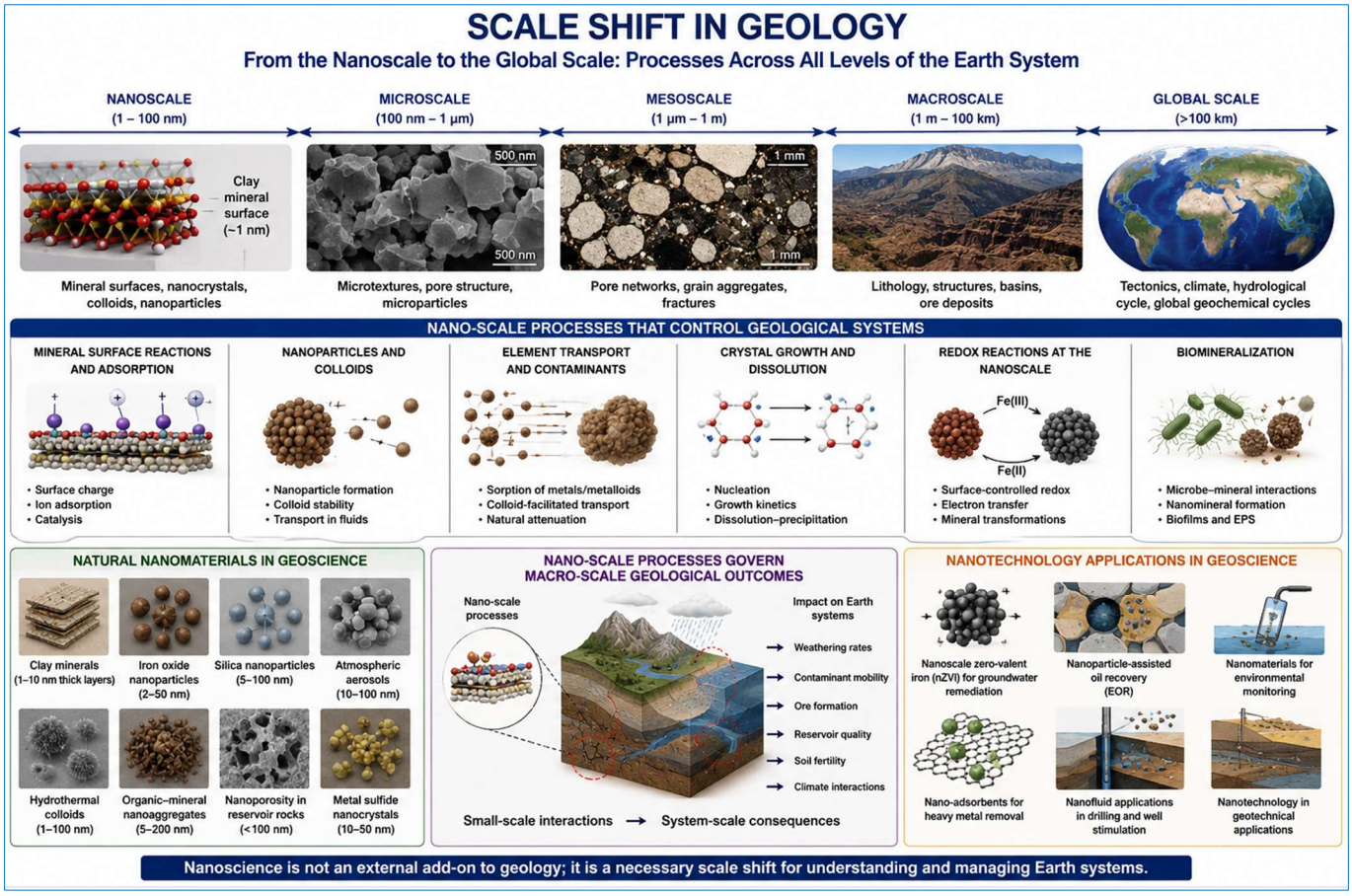

Fig. 2. Scale shift in geology from atomic and nanoscale interfaces to minerals, pores, rocks, reservoirs, and Earth systems (compiled from O'Day, 1999; Navrotsky, 2004; Hochella et al., 2008; Hochella et al., 2019)

Table 1 distinguishes natural, incidental, and engineered nanomaterials in a form useful for geological interpretation. This distinction is not merely semantic. Material origin influences composition, morphology, crystallinity, and initial surface state, whereas environmental history progressively controls the properties that determine subsequent mobility and reactivity. After entering geological environments, nanoparticles may undergo aggregation, dissolution, oxidation–reduction, sulfidation, precipitation, surface passivation, mineral attachment, and interaction with natural organic matter (Babakhani et al., 2017; Liu et al., 2026). Consequently, the particle encountered in groundwater, soil, sediment, reservoir rock, or mine waste may differ substantially from its original form. For example, a freshly synthesized iron nanoparticle used for remediation may rapidly develop oxide shells and natural organic coatings, whereas an iron-rich natural colloid may evolve toward comparable surface-reactive characteristics. A robust interpretation should therefore document not only particle origin and nominal size, but also transformation state, size distribution, mineralogy, morphology, surface chemistry, aggregation state, associated coatings, and the aqueous or

gaseous medium in which the material occurs (Lowry et al., 2012; OECD, 2020).

The central multiscale problem is that nanoscale properties cannot be extrapolated directly to geological performance. High reactivity measured for isolated particles may diminish through aggregation or surface passivation, while apparently minor nanoscale processes can become macroscopically important when repeated across extensive mineral surfaces and interconnected pore networks (Liu et al., 2022; Cao et al., 2025; Wang et al., 2025a). Their field significance therefore depends on coupling between interfacial reaction, pore-scale transport, mineral heterogeneity, fluid flow, and environmental boundary conditions. Establishing these connections requires observations and models that bridge characteristic scales from nanometres and individual interfaces to pores, representative elementary volumes, formations, and ultimately field systems (Wang et al., 2018; Mamtani, 2025). The resulting scale transition, from nanoscale structure and interfacial behavior to pore-scale processes and the field-scale consequences, is illustrated in Fig. 2.

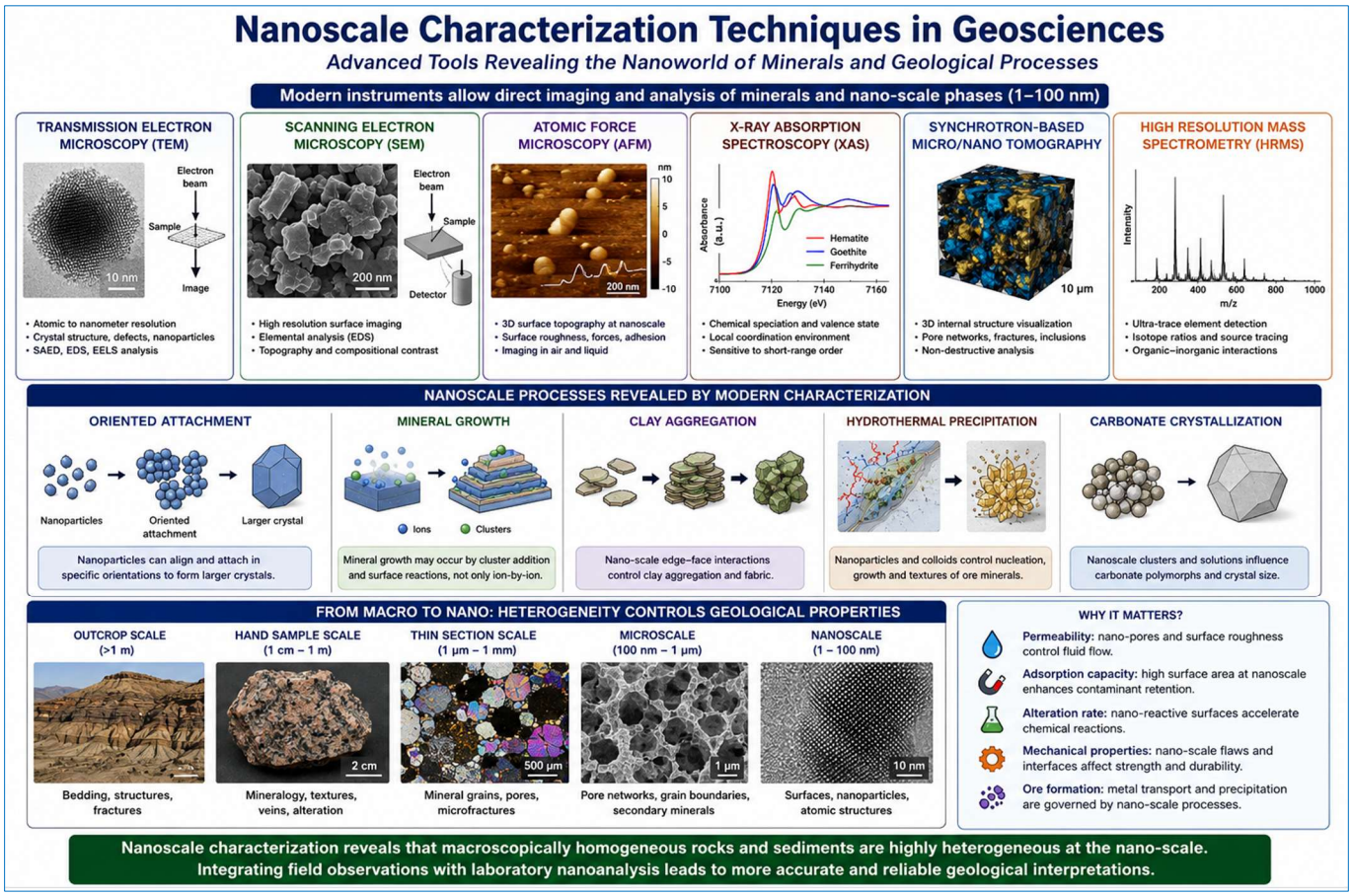

Fig. 3. Nanoscale characterization techniques used to resolve mineral structure, chemistry, surface reactions, and three-dimensional pore architecture (compiled from Penn and Banfield, 1998; O'Day, 1999; Sit et al., 2021; Abdilla et al., 2024; Yang et al., 2024)

3. Nanoscale Thermodynamics and Mineral-Fluid Interfaces

Nanoparticles possess large surface-area-to-volume ratios, making surface free energy a major component of their total energetic state. This affects solubility, phase stability, crystal habits, aggregation, and reaction kinetics. Metastable precursors may therefore persist or transform along pathways that would be poorly predicted from bulk equilibrium alone (Aqra and Ayyad, 2014; Xie et al., 2020; Kushch, 2023; Li et al., 2026a).

Non-classical crystal-growth mechanisms, including oriented attachment, demonstrate that crystals can grow through the alignment and fusion of nanoparticles rather than exclusively by ion-by-ion addition. Such pathways have implications for biomineralization, hydrothermal precipitation, weathering products, and textural interpretation in ore and sedimentary systems (Penn and Banfield, 1998; Navrotsky, 2004; Gilbert and Banfield, 2005).

Mineral-water interfaces are chemically heterogeneous at atomic to nanometre scales. Steps, kinks, vacancies, substitutions, dislocations, terraces, and adsorbed films create distinct sites with different binding energies and reaction probabilities. Recent interface studies show that apparently simple minerals such as quartz and calcite can display spatially variable adsorption and incorporation mechanisms, meaning that a bulk distribution coefficient may average over several competing microscopic processes. This is important when predicting contaminant retention, nutrient mobility, metal uptake, or the evolution of reactive surface area during dissolution (Koretsky, 2000; Fenter and

Sturchio, 2004; Abdilla et al., 2024; Recalcati et al., 2024; Yang et al., 2024).

Fluid–rock reactions are inherently path dependent, meaning that their evolution cannot be predicted solely from initial mineralogy or bulk thermodynamic equilibrium. Local variations in saturation state, reactive-species availability, diffusion through progressively developing alteration layers, changes in reactive surface area, evolving pore geometry, and the nucleation and growth of secondary minerals can cause reaction trajectories to diverge substantially under otherwise similar conditions (Jonas et al., 2013; Zertani et al., 2022). At the nanoscale, dissolution may generate highly reactive surfaces and enlarge pore throats, whereas precipitation, surface coating, and secondary-mineral growth may passivate reactive sites or progressively restrict fluid access to the mineral substrate. These processes create dynamic feedback between reaction and transport, particularly in fractured and porous rocks, where relatively small changes at mineral–fluid interfaces can modify pore connectivity, fracture aperture, tortuosity, and ultimately permeability. Reaction-induced changes in flow pathways can, in turn, redistribute fluids and solutes, altering local residence times and saturation conditions and thereby controlling subsequent reaction rates (Jonas et al., 2013; Beinlich et al., 2020; Filiberto et al., 2023).

Consequently, the geological significance of fluid–rock interaction emerges from a coupled and evolving system in which thermodynamics defines the direction and energetic feasibility of reactions, kinetics controls their rates, pore architecture regulates accessibility and transport, and hydrodynamics determines the continuous redistribution of reactants and products. Surface chemistry is therefore a necessary but insufficient descriptor of fluid–rock reactivity; understanding geological behavior requires resolving the feedback that connects nanoscale interfacial processes to pore-scale evolution and, ultimately, formation-scale transport properties (Filiberto et al., 2023; Deng et al., 2022; Zhang et al., 2024).

4. Characterization: from Imaging to Correlative Nanogeoscience

No single analytical technique can provide particle size, crystal structure, oxidation state, surface chemistry, three-dimensional distribution, and in situ reaction dynamics simultaneously. Transmission and scanning transmission electron microscopy resolve morphology, lattice structure, and nanoscale chemistry; atomic force microscopy measures surface topography and forces in air or liquid; synchrotron X-ray absorption methods constrain element-specific coordination and oxidation state; atom probe tomography can resolve three-dimensional elemental distributions at near-atomic scales; small-angle scattering probes populations that are difficult to image representatively; and single-particle ICP-MS can quantify particle-number and elemental-size distributions in suspensions (Panwar et al., 2020; Jagadeesh et al., 2023; Carsote et al., 2026). Table 2 summarizes these complementary roles.

Methodological strength comes from correlation rather than from maximum nominal resolution. Electron microscopy may provide exquisite images of a tiny, selected volume but can be vulnerable to preparation artifacts and representativeness problems. Spectroscopic measurements may average larger volumes but obscure discrete nanophases. Cryogenic or in situ methods reduce dehydration and beam-induced transformations, while correlative workflows connect mineral texture to chemistry and speciation. Geological studies should therefore design analytical chains around a process question - for example, whether arsenic is structurally incorporated, surface-complexed, or carried by a colloidal phase - rather than selecting techniques primarily for visual impact (O'Day, 1999; Sit et al., 2021). The complementary analytical roles of the principal techniques are synthesized in Fig. 3.

Table 2. Complementary analytical tools for nanogeoscience (synthesized from O'Day, 1999; Sit et al., 2021) and current correlative characterization practice

Method	Main information	Strength	Principal limitation
TEM/STEM-EDS/EELS	Morphology, lattice, nanoscale chemistry and oxidation-state proxies	Direct high-resolution imaging	Small sampled volume; preparation and beam artifacts
AFM	Surface topography, force interactions, growth/dissolution in fluid	Operando surface sensitivity	Limited mineral-volume representativeness
Synchrotron XAS/XRF	Element speciation, coordination, spatial chemistry	Element-specific and often in situ	Facility access; spatial averaging varies by beamline
Atom probe tomography	3D near-atomic elemental distribution	Exceptional chemical resolution	Complex preparation and reconstruction; small volume
SAXS/SANS	Particle/pore size distributions and aggregation	Population-scale statistics	Model-dependent inversion; limited mineral specificity
spICP-MS	Particle number and element-associated size distributions	High-throughput particle-resolved geochemistry	Requires careful calibration and dissolved/particle discrimination
Micro-/nano-CT	3D pore and phase architecture	Links texture to transport geometry	Resolution-volume trade-off; chemistry often indirect

A second requirement is scale-aware sampling. A nanoscale image is not automatically representative of a core, soil horizon, aquifer, or orebody. Sampling should preserve spatial context and ideally connect nano-observations to mesoscopic and field-scale measurements such as porosity, hydraulic conductivity, mineral abundance, bulk geochemistry, or reactive surface area. This nested strategy is especially important for heterogeneous geomaterials, in which rare but highly reactive nanophases can dominate chemical behavior even when they make up a small fraction of total mass (Zhang et al., 2021; Wu et al., 2023; Wang et al., 2025b; Tang et al., 2026).

5. Clay Minerals and Organo-Mineral Interfaces

Clay minerals are intrinsically suited to nanogeoscience because their platelets, interlayers, edge sites, electrical double layers, and adsorbed water films operate at nanometre scales. Smectite, illite, kaolinite, chlorite, sepiolite, and palygorskite differ markedly in layer charge, swelling potential, cation-exchange capacity, specific surface area, and hydration behavior. These differences determine how water, dissolved ions, organic molecules, and contaminants interact with clay surfaces and interlayer domains (Kalkan and Bayraktutan, 2008; Kalkan et al., 2012; Wang et al., 2021; Cosenza et al., 2023; Wang et al., 2024). Particularly in swelling clays, hydration and ion exchange can modify interlayer spacing and surface forces, producing changes in swelling pressure, plasticity, hydraulic conductivity, and mechanical behavior. At the same time, high surface area and abundant reactive sites promote adsorption and ion exchange, making important controls on contaminant mobility, nutrient retention, and aqueous geochemistry. The same nanoscale structural features that contribute to geotechnical problems can therefore be exploited for environmental containment, engineered adsorption, and low-permeability barrier systems (Anderson et al., 2010; Celebi et al., 2012; Bergaya and Lagaly, 2013; Celebi et al., 2016; Ikeagwuani and Nwonu, 2019; Chaudhary et al., 2024).

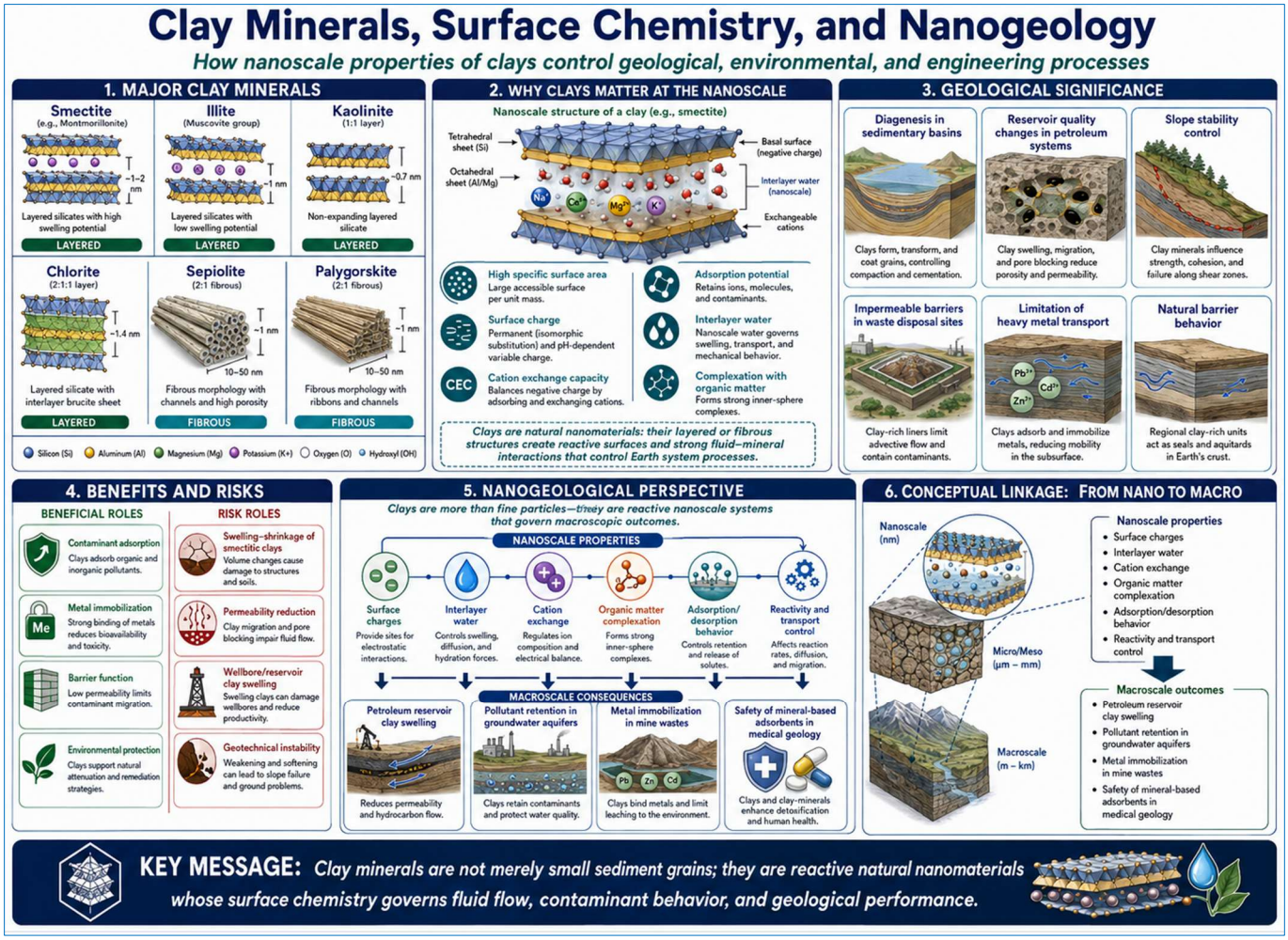

Fig. 4. Clay-mineral surface chemistry and nanoscale controls swelling, ion exchange, adsorption, organo-mineral interactions, and engineering behavior (compiled from Bergaya and Lagaly, 2013; Theng and Yuan, 2008; Kleber et al., 2021)

Water associated with clay surfaces should also not be regarded simply as bulk pore water occupying smaller spaces. Within interlayers and nanopores, mineral surface forces, electrical double-layer interactions, and confinement can modify molecular organization, ion distribution, diffusion, and fluid mobility. Consequently, transport through clay-rich media may become strongly dependent on pore size, surface charge, exchangeable cations, ionic strength, and hydration state (Wang et al., 2022; Cheng et al., 2024). These nanoscale effects provide an important mechanistic link between mineral structure and macroscopically observed properties such as swelling, diffusion, permeability, and solute retardation. They also explain why bulk porosity alone is often insufficient to characterize transport in clay-dominated geological materials (Bourg and Ajo-Franklin, 2017; Whittaker et al., 2020; Huang et al., 2025).

Natural organic matter introduces an additional level of complexity at clay and oxide surfaces. Mineral–organic associations are dynamic interfacial systems rather than passive or permanent coatings. Organic molecules can compete with inorganic ions for adsorption sites, block

existing reactive sites or generate new chemical environments, modify surface charge and aggregation, alter wettability, and influence mineral dissolution and precipitation (Kleber et al., 2021; Kang et al., 2024; Jilling et al., 2025).

Conversely, association with mineral surfaces and confinement within nanoscale pores can reduce the accessibility of organic compounds to microorganisms and extracellular enzymes, contributing to the persistence of organic carbon. At soil and sediment interfaces, carbon stabilization therefore cannot be interpreted solely from bulk organic-carbon concentration. Instead, mineral surface chemistry, pore accessibility, organo-mineral binding, aggregation, and repeated sorption–desorption and redox cycles collectively regulate the accessibility, transformation, and residence time of organic matter (Kleber et al., 2021; Theng and Yuan, 2008). These coupled clay–water and organo-mineral processes are summarized conceptually in Fig. 4.

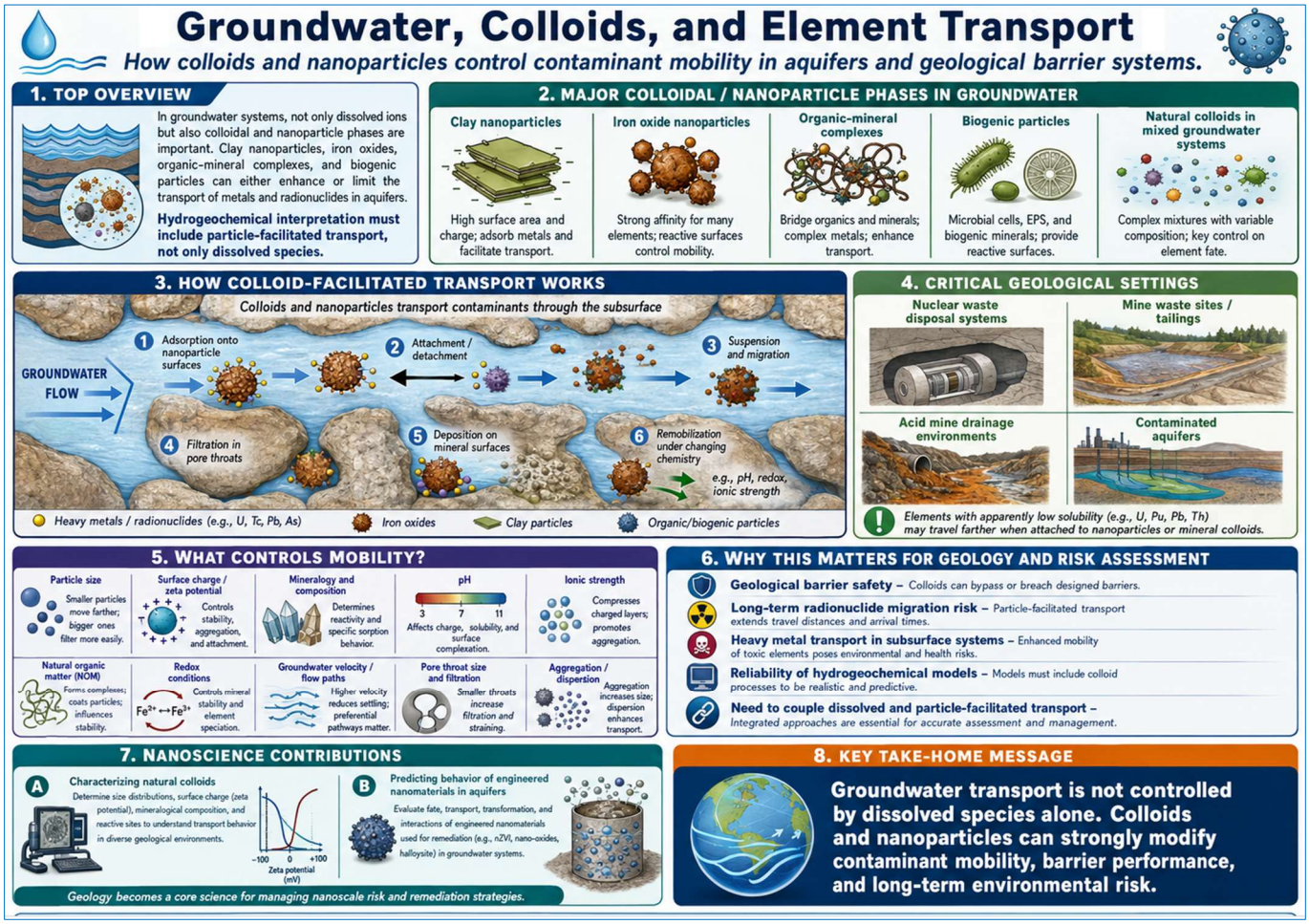

Fig. 5. Groundwater colloids and element transport, including colloid-facilitated migration, filtration, attachment, and geochemical transformation (compiled from Lead and Wilkinson, 2006; Ma et al., 2024; Hennig et al., 2026)

An important implication is that clay-rich systems evolve through feedback among mineral surfaces, pore fluids, organic matter, and microorganisms. Changes in pH, ionic strength, redox state, or solution composition can reorganize surface complexes and mineral–organic associations, while swelling, aggregation, dissolution, or precipitation can modify the pore network itself (Whittaker et al., 2019; Bonnet et al., 2024; Liu and Santamarina, 2025). Such transformations can change both reactive surface area and transport accessibility, meaning that chemical retention and physical confinement cannot always be treated independently. This coupling is particularly important when laboratory-derived adsorption or diffusion parameters are transferred to heterogeneous natural formations over long timescales (Zheng et al., 2022; Chogani et al., 2025).

These concepts are directly relevant to radioactive-waste disposal and other long-lived subsurface barrier systems. Clay formations and compacted clay barriers are attractive because of their low hydraulic conductivity, high sorption capacity, swelling behavior, and potential for diffusive transport to dominate over advection. However, low permeability alone does not guarantee long-term containment (Delage et al., 2010; Sellin and Leupin, 2013; Guimarães and Bobos, 2021). Predictions of contaminant and radionuclide migration must account for diffusion through interconnected nanopores, surface and ion-exchange reactions, mineralogical heterogeneity, pore connectivity, aqueous speciation, and coupled mineral–fluid reactions (Higgo, 1987; Hennig and Kühn, 2023; Assaf et al., 2026). Moreover, changes in pore-water chemistry or mineralogy

over time may alter sorption capacity, diffusivity, and accessible porosity. Reactive-transport calculations for radionuclides in Opalinus Clay illustrate the need to integrate mineral-specific reactions with physically realistic transport parameters when evaluating migration over geological timescales (Hennig et al., 2026).

More broadly, clay minerals demonstrate a central principle of nanogeoscience: macroscopic geological behavior can emerge from the cumulative action of nanoscale interfaces. Swelling pressure, contaminant retardation, carbon stabilization, and extremely low solute transport rates are formation-scale properties, yet each is strongly influenced by processes occurring within interlayers, electrical double layers, nanopores, and mineral–organic interfaces. Establishing this cross-scale connection is essential for transferring molecular- and nanoscale observations into predictive models of natural and engineered geological systems (Ma et al., 2023; Shi et al., 2023; He et al., 2025; Guan and Liu, 2026).

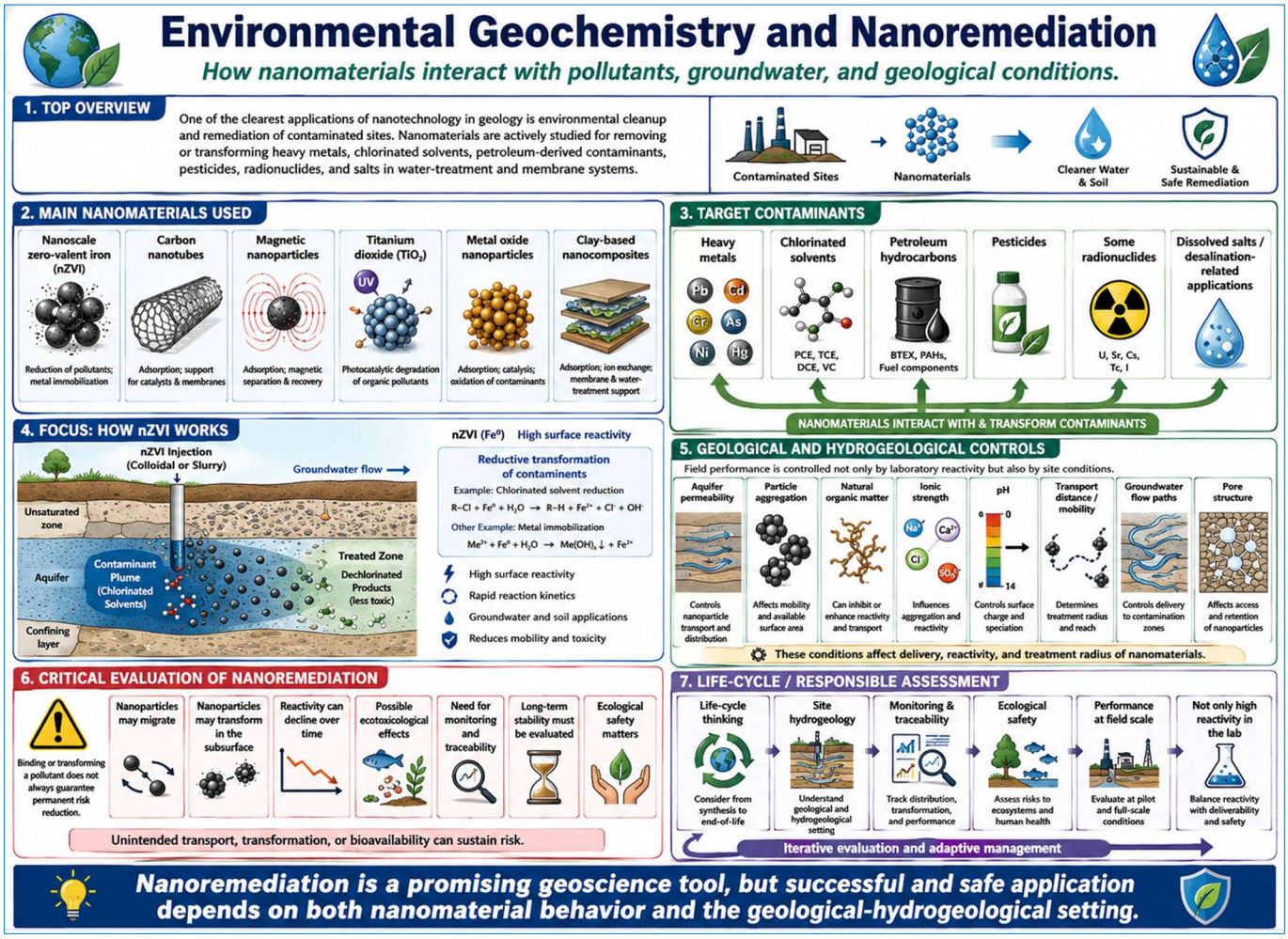

Fig. 6. Environmental geochemistry and nanoremediation: major nanomaterials, contaminant-removal mechanisms, hydrogeological controls, and environmental safeguards (compiled from Karn et al., 2009; Crane and Scott, 2012; Khin et al., 2012; Guerra et al., 2018; Lowry et al., 2012)

6. Environmental Geochemistry, Hydrogeology and Nanoremediation

Groundwater contains a continuum from dissolved species through macromolecules and colloids to suspended particles. This continuum matters because metals and radionuclides can associate with mobile colloids and travel farther than would be predicted from dissolved-speciation models alone. Iron and manganese oxides, clay particles, organic-mineral aggregates, and biogenic particles may either immobilize solutes by sorption or enhance transport when the carrier itself remains mobile. Colloid-facilitated transport is therefore particularly important in contaminated aquifers, mine-waste settings, and assessments of geological disposal systems (Kalkan, 2006; Lead and Wilkinson, 2006; Nami et al., 2021; Ma et al., 2024). The competing mobilization and retention pathways are summarized in Fig. 5.

Engineered nanoparticles have been proposed to exploit the same reactivity for remediation. Nanoscale zero-valent iron is the best-known example, with reduction and sorption pathways applicable to chlorinated compounds and some metals. Other materials include iron oxides, titanium dioxide, carbon-based materials, magnetic particles, and clay-derived nanocomposites. However, laboratory reaction rate is not sufficient for the performance criterion. Aggregation, pore-throat straining, mineral attachment, groundwater ionic strength, pH, dissolved oxygen, natural organic matter, and hydraulic heterogeneity determine

whether a reactive particle reaches the contaminated zone and remains active there (Crane and Scott, 2012; Khin et al., 2012; Guerra et al., 2018). The principal nano-remediation mechanisms and the geological controls are summarized in Fig. 6.

Field implementation should consequently treat nano-remediation as a coupled hydrogeological intervention. Injection pressure, radius of influence, aquifer architecture, residence time, transformation products, and post-treatment monitoring must be designed together. A particle that removes a contaminant from solution may not reduce long-term risk if the contaminant is remobilized during later geochemical changes. Likewise, the nanoparticle itself may transform into phases with different mobility or ecotoxicity. Risk-benefit assessment should therefore include persistence, reversibility, exposure, and life-cycle release rather than focusing only on removal percentage (Karn et al., 2009; Keller et al., 2013; Lowry et al., 2012; Sathish et al., 2024; Mousavi-Kouhi, 2025).

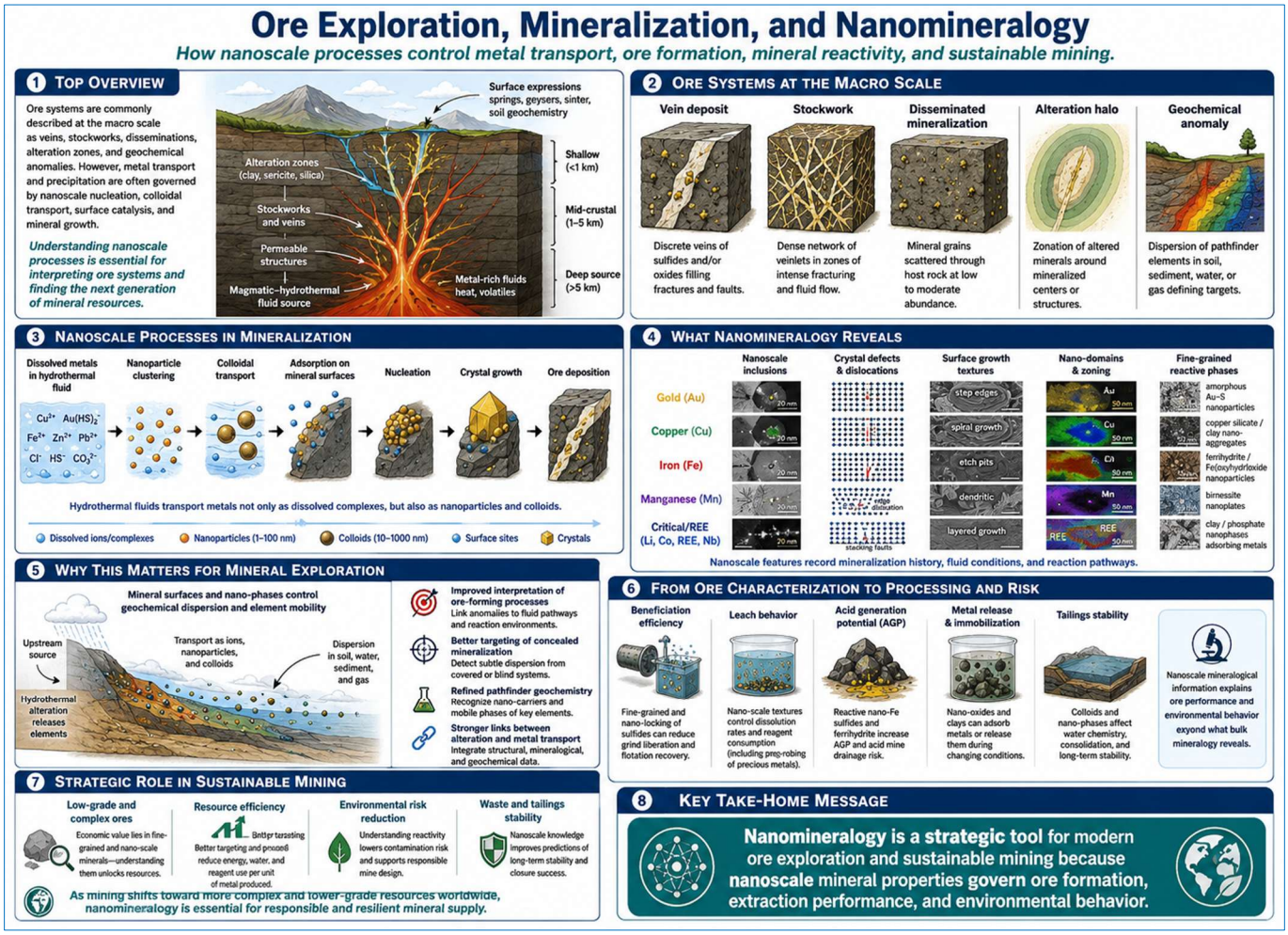

Fig. 7. Ore exploration, mineralization, and nanomineralogy, emphasizing nanoparticle transport, nanoscale mineral hosts, and exploration signals (compiled from Hochella et al., 2019; La Cock and von der Heyden, 2025; Goodman et al., 2025)

7. Ore Systems, Mineral Exploration and Nanomineralogy

Ore-forming systems are traditionally described through hydrothermal fluid chemistry, structural pathways, wall-rock alteration, and precipitation of macroscopic mineral assemblages. Nanogeoscience adds a complementary level of interpretation by resolving metal transport, nucleation, and mineral-host relationships that may remain invisible to conventional bulk analyses (Guan and Liu, 2026).

Metals may nucleate as nanoparticles, be stabilized in colloidal dispersions, absorb reactive mineral surfaces, or become trapped as nanoscale adsorb onto reactive mineral surfaces inclusions and defect-associated enrichments. Because nanoparticles have high surface energies and can respond rapidly to changing fluid conditions, their formation, aggregation, and transformation may record variations in redox state, sulfur activity, fluid mixing, cooling, or supersaturation that are difficult to reconstruct from bulk assays alone (Hochella et al., 2019; Gilbert and Banfield, 2005).

Gold provides a clear example. Direct observations of colloidal gold dispersions in orogenic mineralization support the idea that at least part of hydrothermal metal transport and deposition can involve particulate as well as purely dissolved pathways. This does not replace aqueous-complex models; rather, it broadens the range of mechanisms that can operate during transient supersaturation, rapid physicochemical

change, and fluid-rock interaction (Gartman et al., 2017; Petrella et al., 2020). Nanoparticles may nucleate within hydrothermal fluids and subsequently aggregate, attach to sulfide surfaces, or become incorporated into growing mineral phases. The occurrence, spatial distribution, aggregation state, and mineral association of such particles can therefore provide textural evidence for the sequence and physicochemical conditions of ore formation (Ciobanu et al., 2016; La Cock and von der Heyden, 2025). The links among nanoscale ore processes, mineral hosts, and exploration signals are summarized in Fig. 7.

Nanomineralogy is also important because economically significant elements may occur in forms that are poorly represented by conventional mineralogical descriptions. Trace metals can reside as discrete nanoparticles, nanoscale inclusions, surface-associated species, or structurally incorporated components within larger host minerals. Consequently, two ores with similar bulk elemental concentrations may exhibit substantially different mineral-processing behavior if the target element differs in host phase, particle size, spatial distribution, or degree of encapsulation. Correlative approaches combining high-resolution imaging, spectroscopy, and bulk geochemistry are therefore particularly valuable for distinguishing true nanophases from surface enrichment or submicroscopic inclusions and for linking these occurrences to paragenetic relationships (Plathe et al., 2013; Keith et al., 2023; Guan and Liu, 2026).

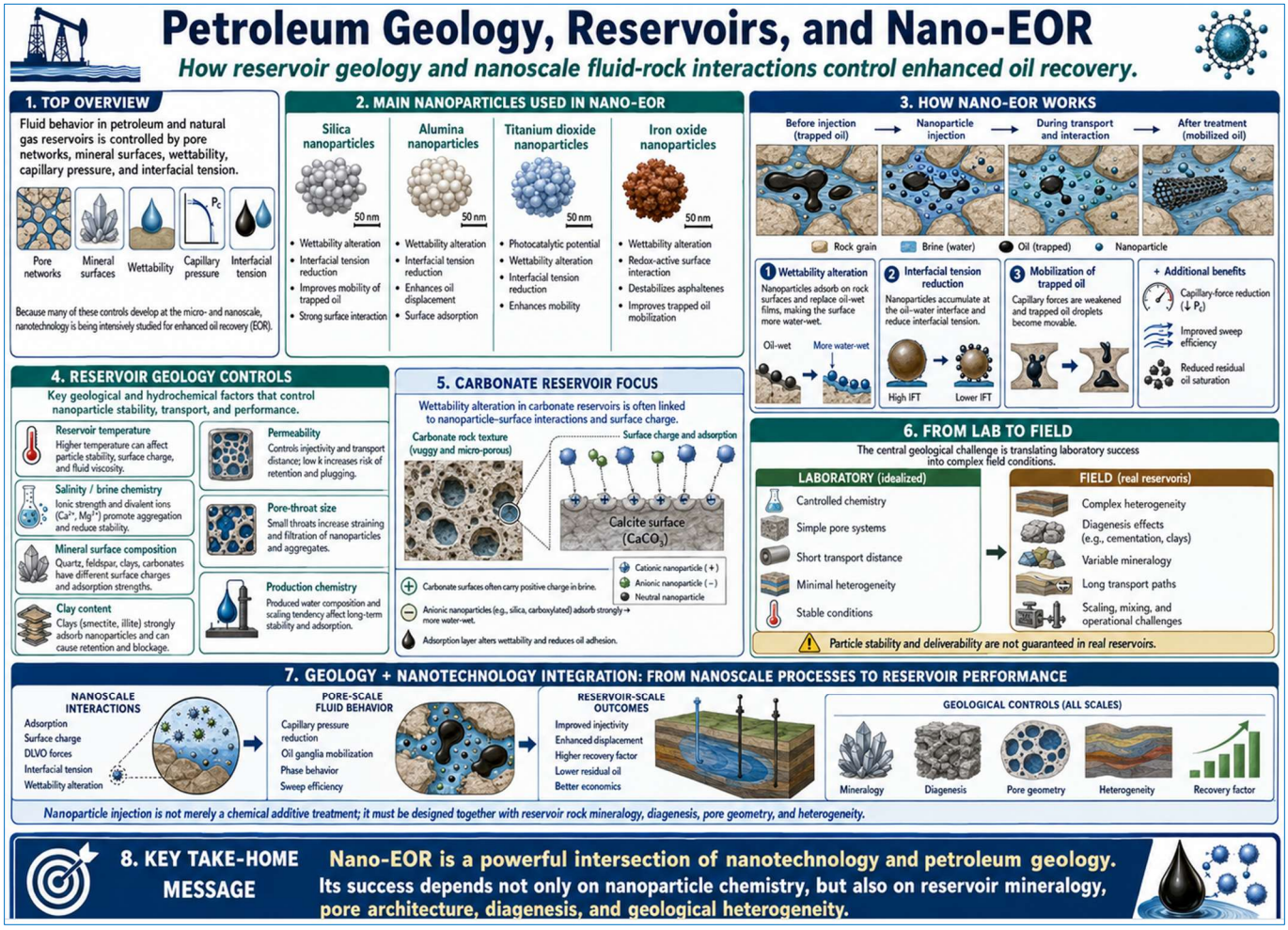

Fig. 8. Petroleum geology, reservoir interfaces, and nanoparticle-assisted enhanced oil recovery mechanisms (compiled from Al-Anssari et al., 2016; Sun et al., 2017; Kandiel et al., 2025)

Nanoparticle information may also provide new exploration vectors. Single-particle ICP-MS can resolve elemental nanoparticles within stream-sediment dispersions and may identify particle populations or element associations that are masked in bulk geochemistry. A recent case study at the Sundance gold mineralization demonstrates the potential of nanoparticle pathfinder geochemistry for detecting mineralization-related signals, while also emphasizing the need to understand sediment transport, background particle populations, sample preparation, and false-positive sources (Hu et al., 2018; Ju et al., 2022; Goodman et al., 2025). From an exploration perspective, the value of such measurements lies not simply in detecting smaller particles, but in determining whether particle composition, abundance, and size distributions preserve information about their mineralized source.

The same nanoscale information has implications beyond discovery. As mining increasingly targets lower-grade and mineralogically complex ores, nanoscale characterization

can improve liberation analysis, leachability prediction, acid-generation assessment, and mine-waste characterization. Fine intergrowths and nanoscale encapsulation may limit physical liberation or reagent access, whereas highly reactive nanophases can disproportionately influence oxidation, metal release, and drainage chemistry despite their small mass fraction. Nanomineralogy can therefore connect ore genesis and exploration with mineral processing and environmental management through a common understanding of mineral hosts and reactive interfaces (Hochella et al., 2008; Civeira et al., 2016; de Vallejuelo et al., 2017; Lütke et al., 2020; Silva et al., 2021; Xing et al., 2023; Yi et al., 2023).

A major limitation, however, is representativeness. Identification of a nanoparticle or nanoscale enrichment within a small analytical volume does not demonstrate that it controls metal transport, ore grade, or an exploration anomaly at deposit scale. Robust interpretation requires nanoscale observations to be linked to paragenesis, bulk mass balance, spatial sampling, and geological architecture. In this sense, the strongest contribution of nanomineralogy is not simply higher analytical resolution, but its ability to connect otherwise unresolved metal-hosting and transport mechanisms with measurable exploration, processing, and environmental signals (Plathe et al., 2013; Silva et al., 2021; Zhang et al., 2026a).

Fig. 9. Geotechnical and rock-mechanics implications of nanoscale fabric, clay-water interactions, nano-cracks, and engineered nanomaterials (compiled from Bergaya and Lagaly, 2013; Diab et al., 2026)

8. Petroleum Reservoirs and Nanoparticle-assisted Recovery

Reservoir performance is governed not only by porosity and permeability but also by interfacial tension, wettability, capillary pressure, surface charge, and pore-scale geometry. Nanoparticles have therefore been investigated as enhanced-oil-recovery agents capable of altering rock wettability, modifying interfacial properties, stabilizing emulsions or foams, and influencing disjoining pressure near three-phase contact regions. Silica is the most extensively investigated material, but alumina, metal oxides, and hybrid particles have also been tested under laboratory conditions (Sun et al., 2017; Bila et al., 2019; Sircar et al., 2022; Kandiel et al., 2025).

Carbonate reservoirs highlight both the promise and the complexity of this approach. Silica nanofluids can shift strongly oil-wet surfaces toward more water-wet conditions, potentially improving spontaneous imbibition and displacement. Yet the magnitude and persistence of wettability alteration depend on brine composition, salinity,

temperature, crude-oil chemistry, mineral surface history, nanoparticle concentration, and stabilizing agents. Laboratory core floods conducted in uniform plugs may therefore overestimate performance in heterogeneous, fractured, or clay-bearing reservoir intervals (Al-Anssari et al., 2016). The main reservoir-scale mechanisms proposed for nanoparticle-assisted recovery are summarized in Fig. 8.

For field translation, retention and injectivity are as important as interfacial reactivity. Nanoparticles can aggregate, absorb irreversibly, bridge pore throats, or react with formation water. A successful formulation must remain transportable through the intended pore network without creating unacceptable formation damage, while still interacting sufficiently with rock and fluids to change recovery mechanisms (Rahham et al., 2024; Liu et al., 2026). The appropriate geological workflow combines mineralogical characterization, pore-size analysis, brine compatibility, high-pressure/high-temperature stability, transport tests, and uncertainty-aware reservoir simulation before pilot injection (Katzourakis and Chrysikopoulos, 2024).

9. Geotechnical Engineering and Nano-structured Geomaterials

Macroscopic geotechnical parameters emerge from processes that may occur at particle contacts and within nanometer-scale water films. In clay-rich soils, diffuse-double-layer forces, interlayer hydration, cation type, edge-face associations, and fabric control swelling, compressibility, shear strength, and permeability. In weak or altered rocks, nano-cracks and fine reactive phases can similarly affect stiffness, time-dependent deformation, and weathering susceptibility. A nanoscale perspective therefore helps explain why specimens with similar grain-size distributions or index properties may respond differently when mineralogy and pore-fluid chemistry differ (Bergaya and Lagaly, 2013; Diab et al., 2026).

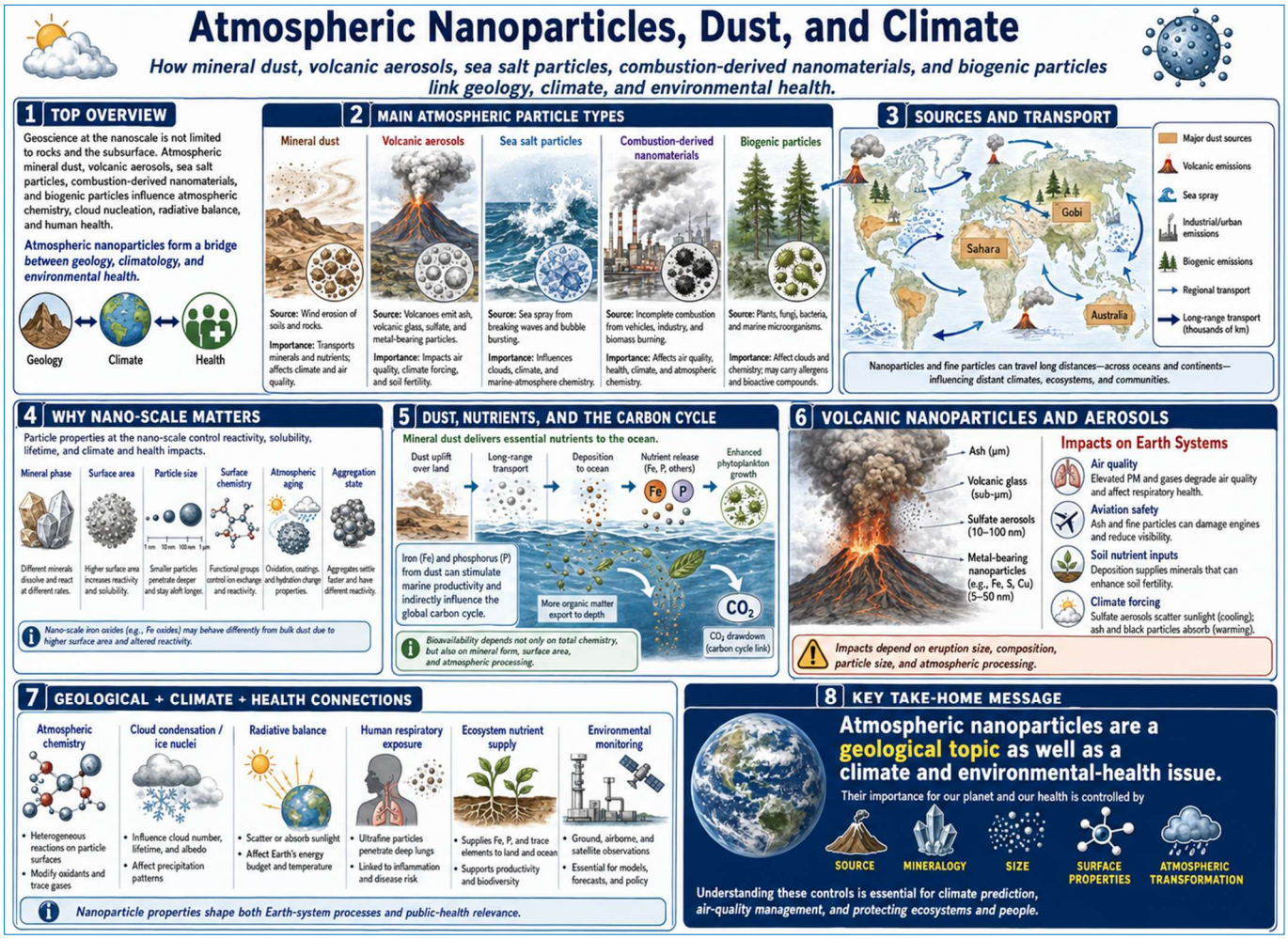

Fig. 10. Atmospheric nanoparticles, mineral dust, aerosols, and climate-related pathways linking geological sources to atmospheric and health processes (compiled from Buseck and Adachi, 2008; Klaine et al., 2008; Hochella et al., 2019)

Engineered nanomaterials are being explored for soil stabilization and cementitious geomaterials. Nano-silica can accelerate pozzolanic reactions and refine pore structure; nano-clay can modify packing and water retention; and reactive nanoparticles can influence cementation or interparticle bonding. Recent critical synthesis emphasizes measurable gains but also warns that performance is highly dependent on dosage, dispersion, soil type, curing, groundwater chemistry, and long-term durability. Environmental release and embodied-energy costs must be

evaluated alongside strength improvement if nano-stabilization is to be considered sustainable (Diab et al., 2026). The resulting nano-to-macro geotechnical relationships are summarized in Fig. 9.

The strongest geotechnical applications will likely be those in which nanoscale characterization explains a known engineering problem rather than merely adding novel material. Examples include diagnosing swelling clay behavior, predicting chemo-mechanical degradation of barriers, understanding grout-rock interfaces, and linking mineral alteration to progressive strength loss. This process-first approach reduces the risk of laboratory optimization that does not survive field heterogeneity.

10. Atmospheric Particles, Soils, Agricultural Geology and Medical Geology

Nanogeoscience extends from the subsurface and terrestrial environments to the atmosphere, where nanoscale particles play important roles in Earth-system processes and environmental quality. Mineral dust, volcanic ash, sea-salt components, combustion-derived particles, and secondary aerosols contain abundant nanoscale phases whose high surface-area-to-volume ratios and chemical reactivity can strongly influence cloud microphysics, atmospheric chemistry, radiative forcing, nutrient transport, and human exposure. During atmospheric transport, these particles may undergo oxidation, dissolution, aggregation, and reactions with acidic or organic species, substantially modifying their mineralogical and surface properties (Hochella et al., 2008; Lee et al., 2019; Ju et al., 2022; Namasivayam et al., 2024; Zhang et al., 2025).

Iron-bearing nanoparticles are particularly important because their mineral form, particle size, and atmospheric processing regulate iron solubility and therefore the potential delivery of bioavailable iron to oceanic ecosystems. Such deposition can influence marine primary productivity and, indirectly, biogeochemical carbon cycling. In addition, nanoscale mineral and metal-bearing particles can act as carriers for adsorbed contaminants and participate in heterogeneous atmospheric reactions, linking geological materials with broader environmental and climatic processes (Shi et al., 2015; Karimdoust et al., 2024; Wzng et al., 2025).

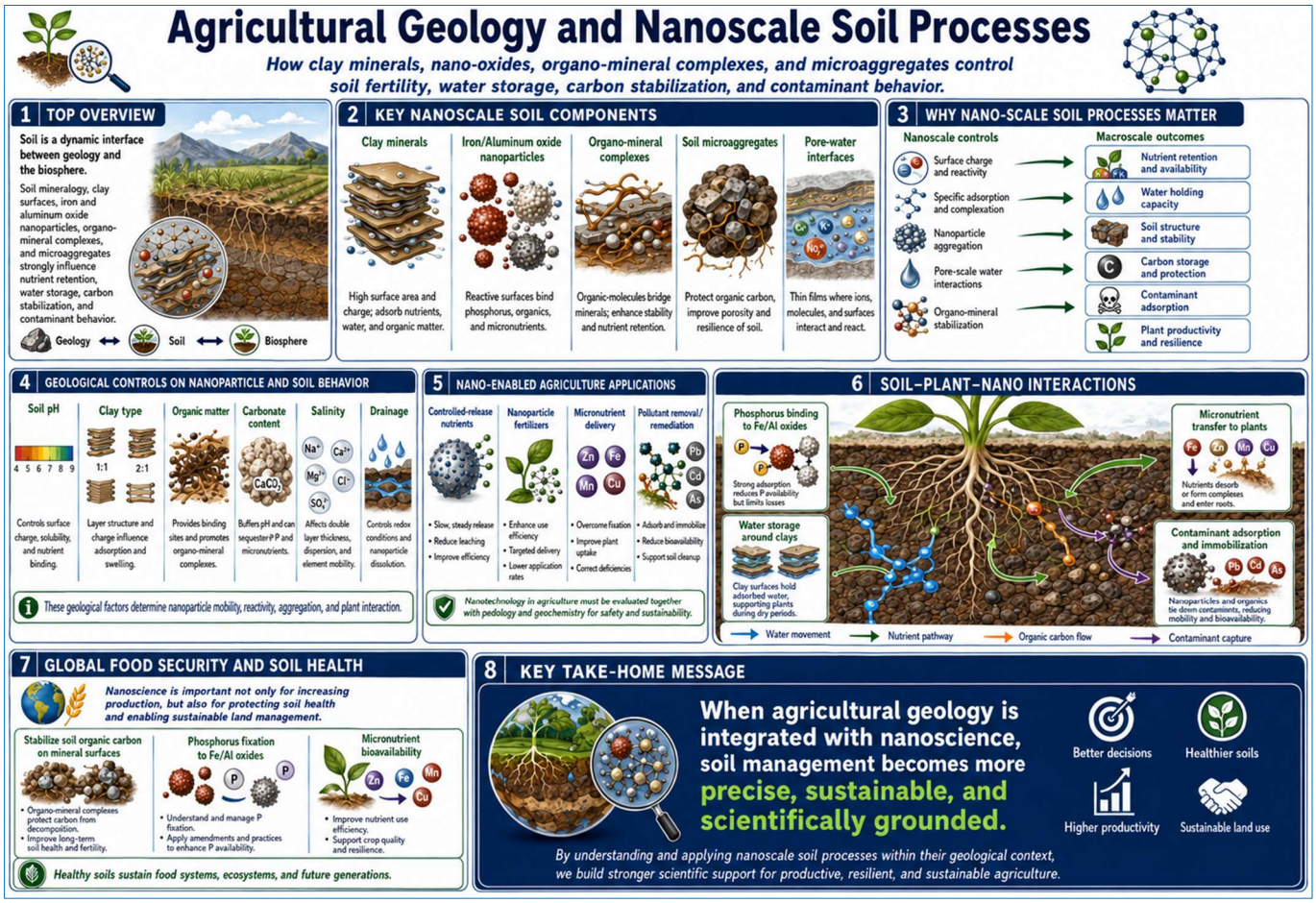

Fig. 11. Agricultural geology and nanoscale soil processes controlling nutrient retention, organo-mineral interactions, trace-element behavior, and soil health (compiled from Theng and Yuan, 2008; Hochella et al., 2019; Kleber et al., 2021)

Atmospheric nanoparticles therefore illustrate the increasingly blurred distinction between natural and incidental nanomaterials, since their final physicochemical characteristics may reflect a combination of geological provenance, long-range atmospheric transformation, and anthropogenic processing (Buseck and Adachi, 2008; Tiwari and Marr, 2010; Hochella et al., 2019; Lespes et al., 2020). Understanding these source–transformation–transport

relationships are essential for evaluating the climatic, ecological, and environmental implications of atmospheric nanomaterials. The major atmospheric sources, transformation pathways, transport processes, and associated consequences are summarized in Fig. 10.

Soils are similarly dominated by highly reactive mineral–water–organic matter interfaces, many of which operate at the nanoscale. Nanoparticulate iron and aluminum oxides, clay minerals, short-range-order phases, and organo-mineral associations exert strong controls on phosphorus retention, trace-element mobility, soil aggregation, carbon stabilization, and water retention and transport. Their high specific surface areas, variable surface charge, and abundant reactive sites promote adsorption, ion exchange, complexation, and precipitation reactions that ultimately govern nutrient availability and contaminant behavior. These nanoscale interactions are also important for the stabilization of soil organic carbon through mineral–organic associations, thereby linking nanogeoscience with terrestrial carbon cycling and soil resilience (Karimdoust, 2022; Theng and Yuan, 2008; Kleber et al., 2021).

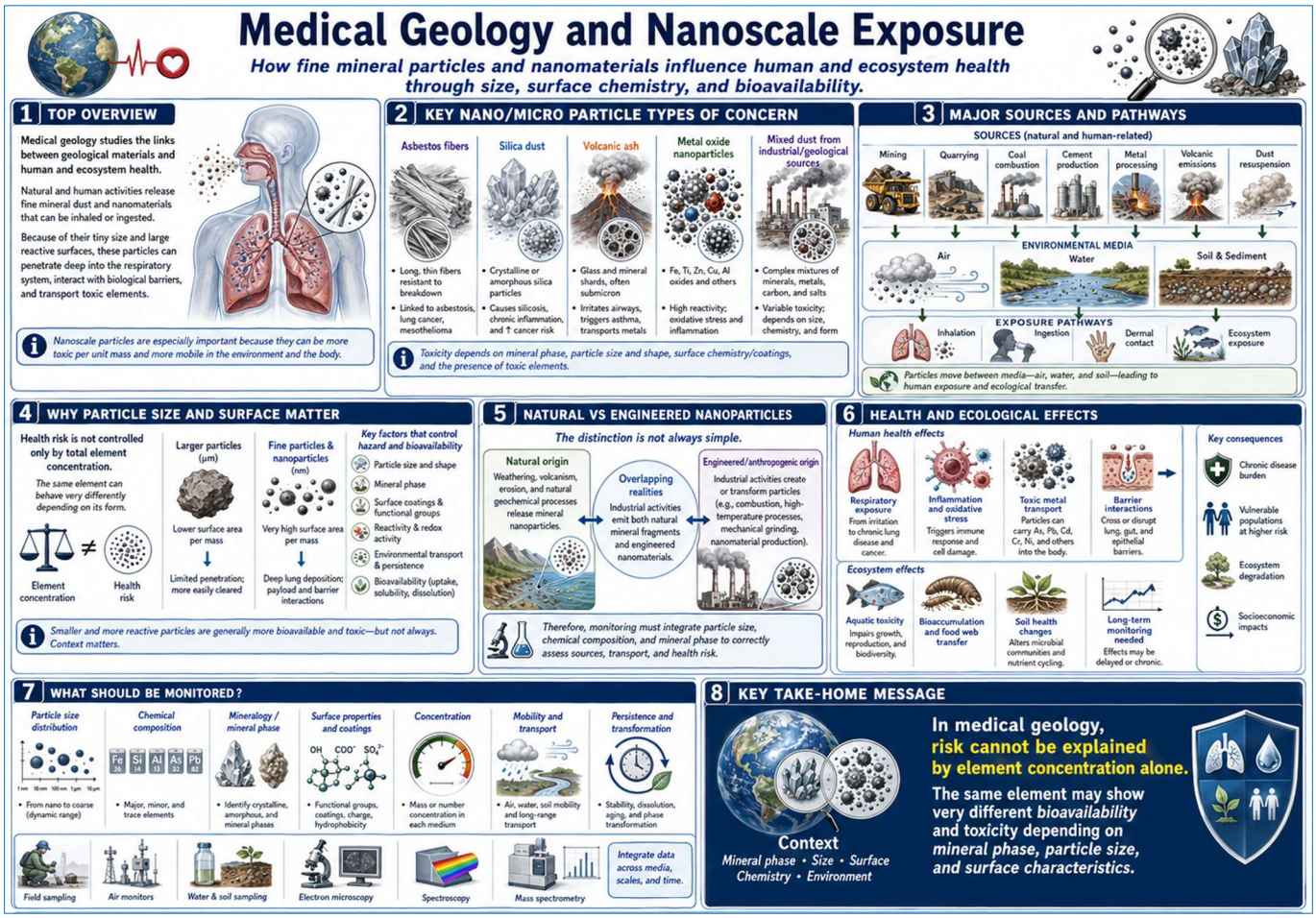

Fig. 12. Medical geology and nanoscale exposure pathways for mineral dust, fibers, metal-bearing particles, and engineered nanomaterials (compiled from Klaine et al., 2008; Lowry et al., 2012; Hochella et al., 2019)

Agricultural nanotechnology introduces an additional dimension through the application of engineered nanoparticles and nano-enabled formulations for controlled nutrient delivery, soil amendment, and contaminant remediation. However, the mobility, persistence, aggregation, dissolution, and biological availability of these materials are strongly controlled by pedological and geochemical conditions, including pH, carbonate content, clay mineralogy, salinity, organic matter, redox fluctuations, and drainage regime. Interactions with natural colloids and mineral surfaces may either enhance nanoparticle retention or facilitate their transport through the soil profile, with potential implications for groundwater quality and ecological exposure (Usman et al., 2020; Strekalovskaya et al., 2024; Haydar et al., 2025; Qiao et al., 2026). Consequently, claims of improved nutrient-use efficiency or remediation performance cannot be generalized across soil types without considering the underlying mineralogical and geochemical context. A soil-specific perspective is therefore essential for predicting both the effectiveness and environmental fate of nano-enabled agricultural technologies. The principal nanoscale controls, transformation processes, and environmental consequences relevant to soils and agricultural geology are summarized in Fig. 11.

In medical geology, particle size introduces a critical dimension beyond total elemental concentration because the biological behavior of geological materials depends strongly on their physical form and surface characteristics. Respirable

crystalline silica, asbestos fibers, metal-bearing dust, volcanic ash, and ultrafine mineral particles may differ substantially in respiratory deposition, dissolution kinetics, surface reactivity, persistence, and biological accessibility (Dolai et al., 2021; Miao et al., 2024). At the nanoscale, increased specific surface area and surface energy can enhance interactions with biological fluids and cellular components, meaning that particles with similar bulk compositions may exhibit markedly different exposure characteristics. Risk interpretation should therefore integrate mineral phase, particle size and morphology, surface coatings, aggregation state, solubility, and associated trace elements rather than relying solely on bulk chemical concentrations (Klaine et al., 2008; Hochella et al., 2019).

The same principle is particularly relevant to mining, quarrying, construction, and other industrial environments, where crushing, grinding, blasting, combustion, smelting, and mineral processing can generate incidental nanoscale and ultrafine particles whose properties may differ substantially from those of the parent rock or ore. Mechanical fragmentation can expose fresh and highly reactive mineral surfaces, whereas high-temperature processes may produce new mineral phases, metal-rich condensates, or complex particle coatings. Once released, these particles may be transported through air, water, or contaminated soils, creating multiple pathways for occupational and environmental exposure (Oberbek et al., 2019; Bessa et al., 2020; Sousa et al., 2021). Consequently, linking geological source, particle-generation processes, nanoscale physicochemical characteristics, environmental transport, and biological accessibility provides a more comprehensive framework for exposure assessment in medical geology (Tomašek et al., 2025). The principal geological exposure pathways and health-relevant nanoscale particle properties are summarized in Fig. 12.

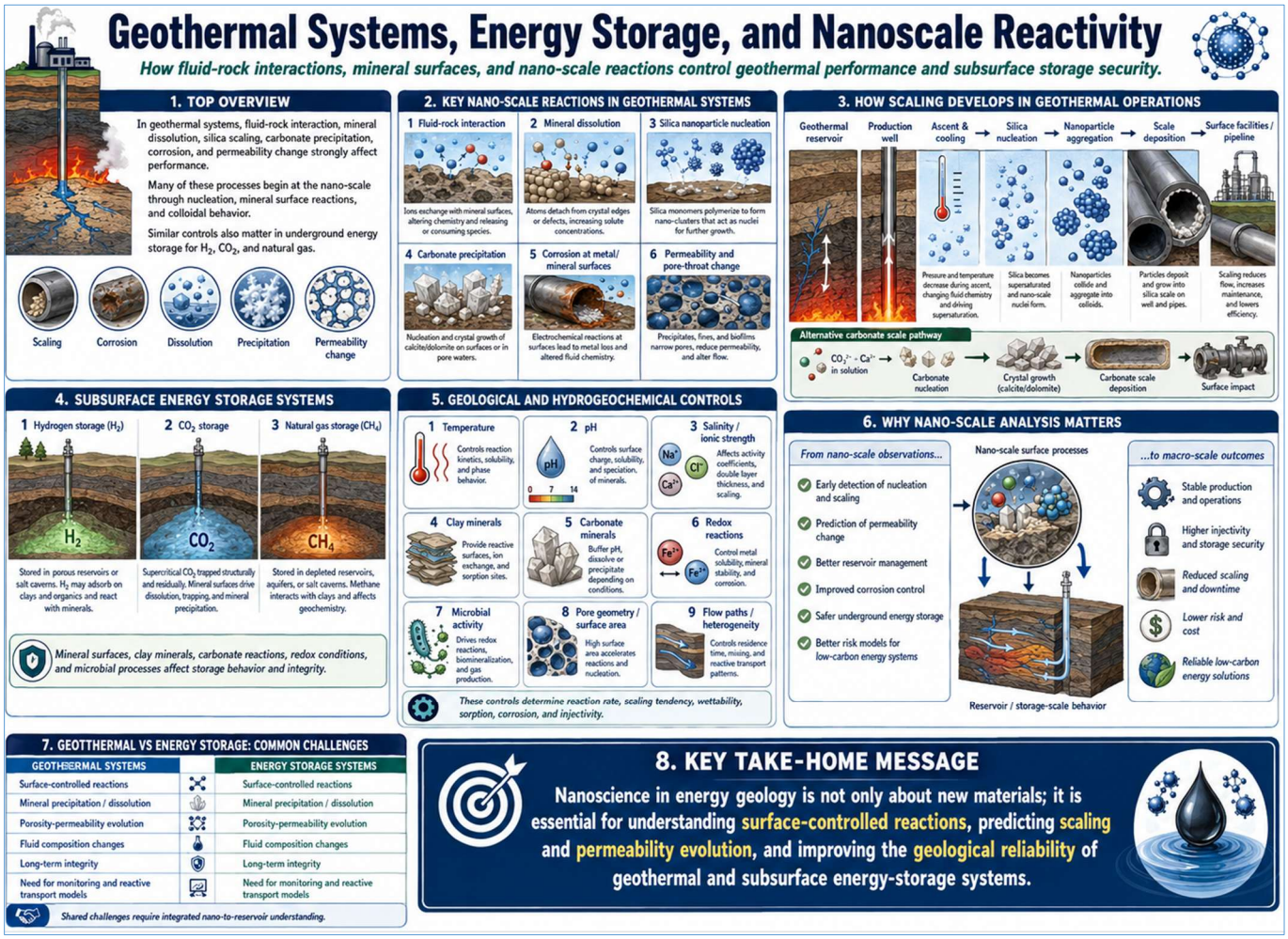

Fig. 13. Geothermal systems, subsurface energy storage, and nanoscale reactivity, including silica nanocolloid formation and nanoconfined multiphase behavior (Steefel and Hu, 2022; Scott et al., 2024; Rezaeyan et al., 2026)

11. Geothermal Systems and Subsurface Energy Storage

Geothermal systems provide a particularly important setting for nanogeoscience because their long-term performance is governed by coupled thermal, hydraulic, chemical, and mineralogical processes occurring across multiple spatial scales. During production and reinjection, changes in temperature, pressure, pH, redox conditions, and fluid composition can disturb water–rock equilibrium and trigger mineral dissolution, precipitation, and colloid formation. These reactions can progressively modify fracture apertures, pore connectivity, permeability, and heat-transfer efficiency, thereby linking nanoscale interfacial processes directly to

reservoir-scale hydraulic performance (Kalkan et al., 2012; Soltani et al., 2022; Meng et al., 2025; Mousavi et al., 2026).

Silica scaling is a classic example of this multiscale behavior. Cooling, depressurization, evaporation, or fluid mixing may generate supersaturation with respect to silica, but macroscopic scale formation is commonly preceded by molecular polymerization, nucleation, and the growth and aggregation of silica nano-colloids (Yao et al., 2023; Kaneda et al., 2024). Consequently, the transition from dissolved silicic species to colloidal silica and ultimately to adherent deposits is fundamentally a nanoscale kinetic and interfacial process. Nanoparticle size, surface charge, aggregation behavior, fluid residence time, ionic strength, and interactions with mineral or infrastructure surfaces may all influence whether silica remains dispersed or develops into operationally significant scale.

Understanding these mechanisms can improve predictions of scaling in separators, heat exchangers, pipelines, reinjection wells, and reservoir near-wellbore zones and can support more effective scale-control strategies. Experimental investigations of silica polymerization and nano-colloid growth therefore provide an important mechanistic basis for linking geothermal fluid chemistry with the initiation and evolution of mineral scale (Scott et al., 2024).

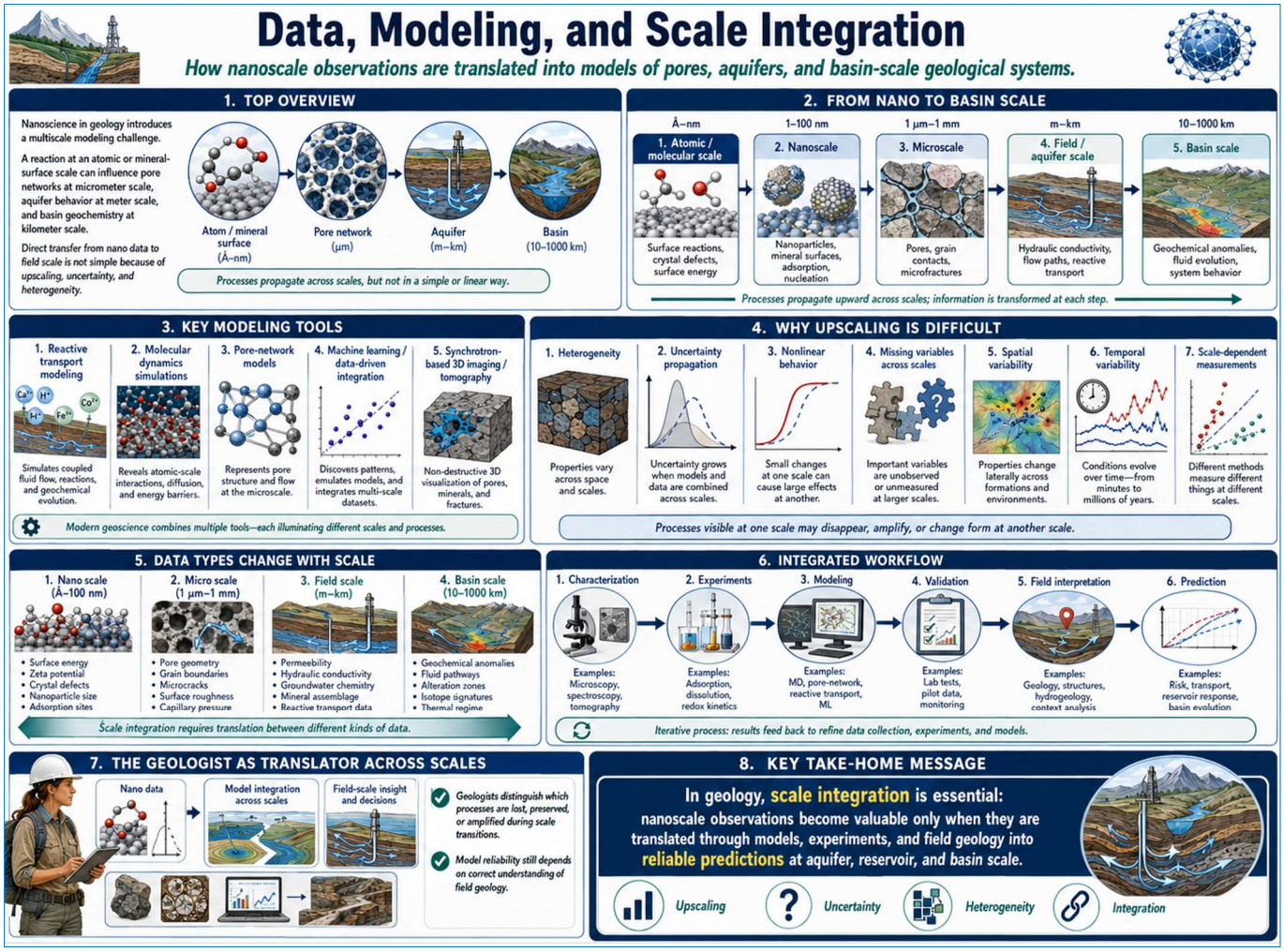

Fig. 14. Data, modeling, and scale integration in nanogeoscience, from molecular mechanisms and pore-scale structure to reactive-transport prediction (compiled from Deng et al., 2022; Steefel and Hu, 2022; Zhang et al., 2024)

Nanoscale processes are equally relevant to geological carbon storage and other emerging forms of subsurface energy storage. CO_2 dissolution, capillary trapping, mineral carbonation, wettability alteration, and multiphase flow occur within heterogeneous pore networks in which a significant fraction of the pore space may approach micro- to nanometre dimensions. Under such confinement, mineral surface chemistry, interfacial tension, contact angle, and pore geometry can modify fluid distribution and phase behavior relative to bulk-fluid conditions. Recent experimental evidence for CO_2 nanobubble exsolution and associated hysteresis in water-saturated sandstone further demonstrates that confinement and mineral–fluid interfaces can generate behavior that is not adequately represented by simple bulk thermodynamic assumptions (Youns et al., 2023; Pang et al., 2024; Rezaeyan et al., 2026).

Such effects may influence residual trapping efficiency, CO_2 dissolution kinetics, pressure evolution, and the interpretation of injection–shut-in–reinjection cycles. More

broadly, these observations emphasize that subsurface energy technologies cannot be fully understood from reservoir-scale parameters alone. Nanoscale mineral–fluid interactions can propagate upward in scale by altering wettability, pore accessibility, reactive surface area, precipitation–dissolution patterns, and ultimately permeability and storage efficiency. Incorporating these mechanisms into reactive-transport and reservoir models may therefore improve predictions of injectivity, storage security, operational longevity, and geochemical evolution (Shi et al., 2023; Chogani et al., 2025; Zhang et al., 2026b). This perspective is relevant not only to geothermal energy and geological CO_2 storage but also to emerging subsurface energy-storage systems involving gases such as hydrogen, where confinement, mineral reactivity, and interfacial processes may similarly control long-term performance (Yekta et al., 2018; Kiliç et al., 2022). The principal nanoscale mechanisms linking mineral–fluid reactions, pore-scale processes, and operational consequences in geothermal and subsurface energy systems are summarized in Fig. 13.

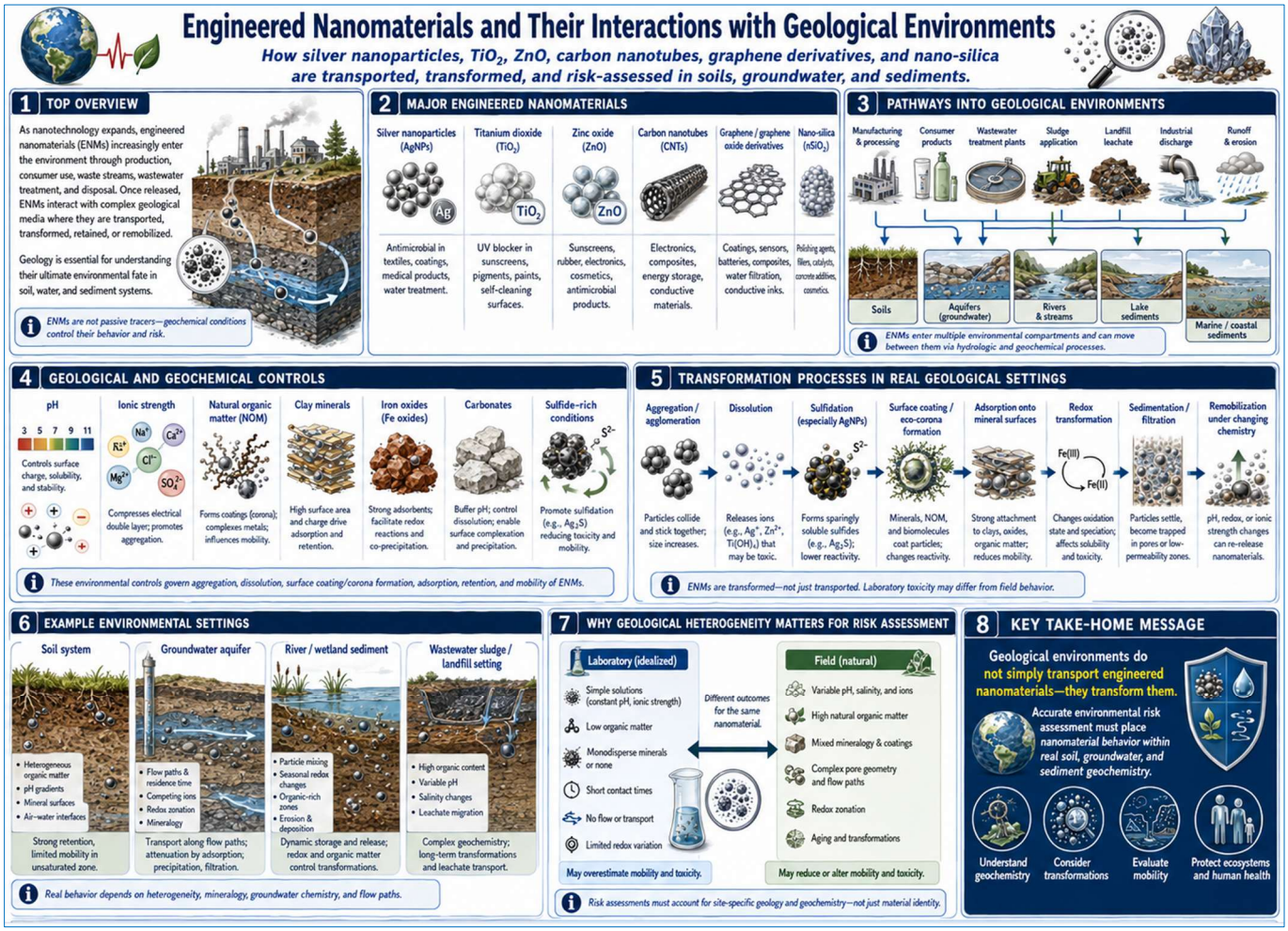

Fig. 15. Transformation and fate of engineered nanomaterials in geological environments through aggregation, dissolution, surface coating, mineral attachment, and transport (compiled from Lowry et al., 2012; Keller et al., 2013; Hochella et al., 2019)

Similar interface-sensitive processes are expected to influence underground hydrogen storage (UHS) and other emerging subsurface-energy technologies, although the experimental and field-scale evidence base remains considerably less mature than for conventional gas storage or geological CO_2 sequestration. In porous reservoirs, hydrogen migration, retention, and recovery are controlled not only by bulk pressure and temperature but also by pore-scale and nanoscale interactions at mineral–brine–gas interfaces (Lysyy et al., 2022; Oliver et al., 2024). Mineral wettability and contact-angle behavior directly influence capillary trapping and gas mobility, while capillary entry pressure and pore-throat geometry determine whether hydrogen can penetrate or escape through low-permeability sealing formations. Clay swelling, mineral dissolution–precipitation reactions, and changes in surface charge may further modify pore connectivity and permeability during repeated injection–withdrawal cycles (Perera, 2023; Wang et al., 2026).

Geochemical and biological processes introduce additional complexity. Hydrogen is highly reactive in certain subsurface environments and may participate in redox reactions involving iron-bearing minerals, sulfates, or other reactive phases. Microbial consumption of H_2 can alter gas composition and generate secondary products such as methane or hydrogen sulfide, potentially affecting storage efficiency, gas quality, and infrastructure integrity (Dopffel et

al., 2021; Bade et al., 2024; Tinker et al., 2025; Vedadi et al., 2026).

Gas dissolution into formation water, diffusion through water-filled nanopores, and interactions with mineral surfaces may also contribute to hydrogen losses and influence long-term containment. These mechanisms are strongly dependent on mineralogy, brine chemistry, pore architecture, microbial communities, and pressure–temperature conditions and therefore require an integrated geochemical and pore-scale perspective (Bo et al., 2021; Jangda et al., 2023; Khan et al., 2024).

Fig. 16. Ethics, risk, and governance framework for nanomaterial use in geological and environmental applications (compiled from Karn et al., 2009; Lowry et al., 2012; OECD, 2020; ISO, 2023)

The broader lesson is that nanoscience in subsurface energy systems should not be viewed simply as the intentional injection of engineered nanoparticles into reservoirs. Its more fundamental contribution lies in resolving the interfacial physics and chemistry that govern fluid–mineral interactions at the smallest relevant scales and determining how these processes propagate toward reservoir-scale behavior. By linking nanoscale wettability, surface reactions, confinement effects, and mineral transformations with macroscopic transport and mechanical properties, nanogeoscience can improve understanding of gas storage and recovery, scaling and precipitation, caprock sealing, leakage potential, and long-term reservoir integrity (Panchal et al., 2021; Steefel and Hu, 2022). Such a multiscale perspective will be increasingly important for evaluating the feasibility and reliability of underground hydrogen storage and other subsurface technologies supporting the transition toward low-carbon energy systems.

12. Multiscale Modeling and Data Integration

The central challenge in nanogeoscience is upscaling: translating molecular- and nanoscale observations into predictive models that remain valid at the pore, core, reservoir, and field scales. A reaction rate or surface process measured on an idealized crystal face cannot be transferred directly to a heterogeneous rock system. At larger scales, the effective behavior of a mineral–fluid system is controlled not only by its intrinsic reactivity, but also by mineral abundance and distribution, reactive surface accessibility, pore connectivity, flow focusing, diffusion limitations, evolving porosity and permeability, and the distribution of fluid residence times (Bercovici et al., 2024; Ngoma and Kolawole, 2024). Consequently, the apparent reaction behavior observed at the field scale may differ substantially from that inferred from idealized laboratory experiments. Reactive-transport modeling provides a formal framework for integrating aqueous speciation, mineral dissolution and

precipitation, sorption, and fluid transport; however, the predictive reliability of such models is often limited by parameter uncertainty and by the difficulty of transferring laboratory-derived parameters to field-relevant conditions (Deng et al., 2022).

A robust multiscale strategy therefore requires hierarchical integration rather than direct parameter extrapolation. Digital-rock methods and three-dimensional imaging can provide realistic representations of pore geometry, mineral distributions, and evolving pore structures. Pore-network and pore-scale reactive-transport models can then translate mineral-scale reaction kinetics into effective transport and reaction parameters while explicitly accounting for local flow heterogeneity and diffusion limitations. Molecular simulations, including density functional theory and molecular dynamics, can further identify plausible reaction pathways, adsorption configurations, interfacial structures, and energetically favorable surface processes. Surface-complexation and thermodynamic models provide an additional intermediate level at which molecular-scale mechanisms can be expressed in terms of experimentally measurable macroscopic quantities such as surface charge, adsorption capacity, and aqueous speciation (Molins et al., 2019; Noiriel and Soulaine, 2021).

These approaches are most powerful when linked through a scale-aware parameter-passing framework. Molecular calculations can constrain reaction mechanisms and energetics; nanoscale experiments can provide information on surface reactivity and interfacial processes; pore-scale simulations can determine how these processes are modified by mineral heterogeneity, confinement, and local transport; and continuum reactive-transport models can propagate the resulting effective parameters to core and field scales. In this framework, upscaling should not be understood as the simple averaging of nanoscale properties. Instead, the objective is to identify which microscopic properties remain scale-invariant, which must be transformed into effective parameters, and which emerge only from interactions between reaction and transport (Karimi and Bhattacharya, 2023). The hierarchy linking nanoscale observations to field-scale predictions is summarized in Fig. 14.

Machine learning (ML) can strengthen this hierarchy when it is used as a complementary tool rather than as a replacement for mechanistic geochemical modeling. ML models can function as fast emulators of computationally expensive molecular or pore-scale simulations, identify nonlinear relationships within large experimental datasets, classify alteration patterns, and quantify parameter uncertainty. Their performance is likely to be more robust when models are trained using physically meaningful descriptors—such as mineral composition, surface area, pore-size distribution, fluid composition, temperature, pH, ionic strength, saturation state, and flow conditions—rather than relying solely on unconstrained statistical correlations.

Physics-informed machine learning and hybrid models that embed conservation laws, thermodynamic constraints, or reaction kinetics within data-driven architecture offer a particularly promising route for combining the predictive flexibility of ML with the interpretability and physical consistency of mechanistic models.

An important consequence of this approach is that data integration must occur across both scale and modality. Imaging data, spectroscopic observations, molecular calculations, laboratory reaction experiments, pore-scale simulations, and field monitoring data describe different aspects of the same coupled system. Their integration requires common descriptors, consistent thermodynamic conventions, uncertainty propagation, and careful distinction between directly measured quantities and inferred model parameters. Bayesian calibration, ensemble modeling, and global sensitivity analysis can be used to identify which parameters exert the greatest influence on field-scale predictions and where additional experiments would most effectively reduce uncertainty (Prasianakis et al., 2025). Such approaches can also reveal whether uncertainty originates primarily from intrinsic reaction kinetics, poorly constrained surface properties, unresolved pore-scale heterogeneity, or uncertainties in transport and boundary conditions.

Model validation must be performed at the scale at which predictions are ultimately intended to be used. Agreement between a nanoscale simulation and a spectroscopic observation, for example, does not by itself demonstrate that a field-scale reactive-transport model is reliable. Validation should therefore rely on independent observables that capture the emergent behavior of the target system. Relevant observables include breakthrough curves, effluent chemistry, mineral saturation indices, changes in porosity and permeability, tracer-response characteristics, reaction-front migration, and spatial patterns of mineral alteration. Ideally, validation should be performed simultaneously against multiple observables so that a model cannot reproduce one measurement through compensating errors in unrelated parameters (Latrille et al., 2021).

Studies of fractured and heterogeneous rocks further demonstrate why this multiscale perspective is necessary. Microporosity, mineralogical texture, fracture connectivity, and spatial variations in reactive surface area can strongly influence fluid access and the location and progression of reaction fronts (Andrews et al., 2023; Zhang et al., 2024). A mineral may therefore possess high intrinsic nanoscale reactivity while contributing relatively little to bulk reaction if its reactive surfaces are inaccessible to flowing fluids. Conversely, minerals with apparently modest intrinsic reactivity may exert a major influence on system-scale behavior when they are abundant, well connected to the flow network, or positioned within preferential transport pathways (Beckingham et al., 2016; Seigneur et al., 2019; Guan and Liu, 2026).

Ultimately, the goal of multiscale modeling is not to collapse all scales into a single universal model, but to establish a physically defensible chain of information transfer between scales. Each modeling level should retain the information that is relevant to the next level while explicitly representing the uncertainty introduced during coarse-graining and

homogenization. Such a framework enables nanoscale mechanisms to inform effective pore-scale properties, pore-scale behavior to constrain continuum-scale parameters, and field observations to provide feedback for refining lower-scale models (Soulaine and Tchelepi, 2016; Ashworth et al., 2022). This iterative integration of experiment, simulation, imaging, and data-driven methods provides a pathway toward more predictive and uncertainty-aware models of coupled mineral–fluid processes in natural and engineered geosystems.

13. Environmental Risk, Standards and Responsible Deployment

The distinction between natural, incidental, and engineered nanomaterials has regulatory and ethical consequences because intentional deployment creates an obligation to understand exposure and transformation. Engineered particles may dissolve, oxidize, sulfidize, aggregate, acquire biomolecular or mineral coatings, or become immobilized on sediment surfaces. Toxicity measured for a pristine material may therefore overestimate or underestimate risk after environmental aging. Conversely, transformation does not guarantee safety: it may generate mobile dissolved species or change bioavailability (Klaine et al., 2008; Lowry et al., 2012; Kumar et al., 2022; Nath, 2026). Transformation pathways of engineered nanomaterials in geological media are summarized in Fig. 15.

Standardized reporting is essential if laboratory studies are to support field decisions. ISO 80004-1 provides core nanotechnology vocabulary, while OECD guidance addresses dissolution and dispersion stability relevant to environmental testing. At minimum, studies should report particle identity, primary and hydrodynamic size, size distribution, aggregation state, surface chemistry, crystal phase, dose metrics, medium chemistry, preparation method, and temporal transformation. For geological applications, these should be supplemented by mineralogy, pore-water chemistry, porosity/permeability, temperature, pressure where relevant, and a mass-balance or recovery assessment (ISO, 2023; OECD, 2020; Malvoisin et al., 2021; Guan and Liu, 2026).

Table 3 summarizes a risk-aware decision framework. The critical principle is reversibility: before subsurface injection, investigators should ask not only whether a nanomaterial works, but what happens if it migrates beyond the target zone, loses reactivity, desorbs the contaminant, or produces transformation products. Monitoring should be designed around plausible failure modes and should continue long enough to observe delayed changes. This framework aligns technological innovation with geological stewardship rather than treating environmental assessment as an afterthought (Karn et al., 2009; Keller et al., 2013). The corresponding risk and governance framework is summarized in Fig. 16.

14. Research Priorities for the Next Phase of Nanogeoscience

First, nanogeoscience needs reference materials and interlaboratory protocols that better represent complex natural matrices. Many published experiments use monodisperse particles, simple electrolytes, or ideal mineral surfaces, whereas soils, brines, mine waters, and reservoir fluids contain multivalent ions, organic matter, mixed minerals, microorganisms, and fluctuating redox conditions. Bridging this gap requires benchmark natural samples, agreed metadata, and systematic reporting of uncertainty (Guarena et al., 2022). Without such comparability, differences among studies may reflect preparation methods as much as underlying geology (OECD, 2020; Sit et al., 2021).

Table 3. Risk-aware decision framework for subsurface use of engineered nanomaterials (synthesized from Karn et al., 2009; Lowry et al., 2012; OECD, 2020; ISO, 2023)

Decision stage	Minimum geological question	Evidence required	Stop/go criterion
Material selection	Is the material compatible with formation minerals and fluids?	Mineralogy, brine chemistry, surface characterization, stability tests	No rapid aggregation, deleterious reaction, or unacceptable dissolution
Transport	Can the material reach the target without formation damage?	Column/core transport, retention, pressure response, particle recovery	Adequate radius of influence and acceptable injectivity
Function	Does the intended mechanism operate under field conditions?	HP/HT or site-realistic tests, reaction kinetics, mass balance	Effect persists at realistic residence time and concentration
Risk	What transformations and off-target exposures are plausible?	Transformation products, toxicity/exposure screen, reversibility	Risk is bounded and monitorable
Monitoring	Can success and failure modes be detected?	Baseline geochemistry, tracers, hydraulic and chemical monitoring	Measurable indicators and defined intervention thresholds

Second, more measurements are needed under realistic pressure, temperature, salinity, and stress. This is especially important for geothermal systems, deep aquifers, hydrocarbon reservoirs, CO2 storage, and engineered barriers. In situ and operando experiments should be paired with post-reaction microscopy and spectroscopy so that transient species can be related to final textures. The recent shift toward dynamic interface measurements and nanoconfined-fluid observations shows the value of this approach (Hellmann et al., 2012; Abdilla et al., 2024; Rezaeyan et al., 2026).

Third, field validation must become a publication priority rather than a late commercialization step. Laboratory demonstrations of nanoparticle transport, remediation, EOR, or stabilization should be evaluated using mass recovery, spatial monitoring, hydraulic response, and long-term geochemical stability in representative geological settings. Negative or conditionally successful trials are scientifically valuable because they define the boundaries of applicability. Finally, research should integrate benefit and risk in the same experimental design. The most useful future

studies will quantify not only efficiency but also material persistence, transformation, resource intensity, reversibility, and uncertainty across scales (Kumah et al., 2023; Bouhadi et al., 2025; Qiao et al., 2026). The broader transformation of geological reasoning enabled by nanoscience is summarized in Fig. 17.

15. From Nanoscale Evidence to Geological Decisions

An integrated nanogeoscience workflow should begin with a geological decision rather than with an instrument or nanomaterial. The decision may concern whether an aquifer contaminant will remain immobilized, whether a fine-grained ore will respond to a given beneficiation route, whether a nanofluid can be injected without permeability loss, or whether a clay-rich seal will retain its integrity during chemical perturbation. Once the decision is defined, the nanoscale hypothesis can be formulated explicitly (Ju et al., 2017; Mamtani, 2025; Zhao et al., 2026). This prevents a recurring weakness in the literature in which a striking nanoscale observation is documented without demonstrating whether it controls a property that matters at core, reservoir, catchment, or basin scale. A useful hypothesis therefore links a mechanism, an observable, and a scale transition: for example, surface-complexation heterogeneity may alter desorption kinetics, which in turn changes a breakthrough curve under a defined flow regime (Guimarães et al., 2016; Pettersson et al., 2024).

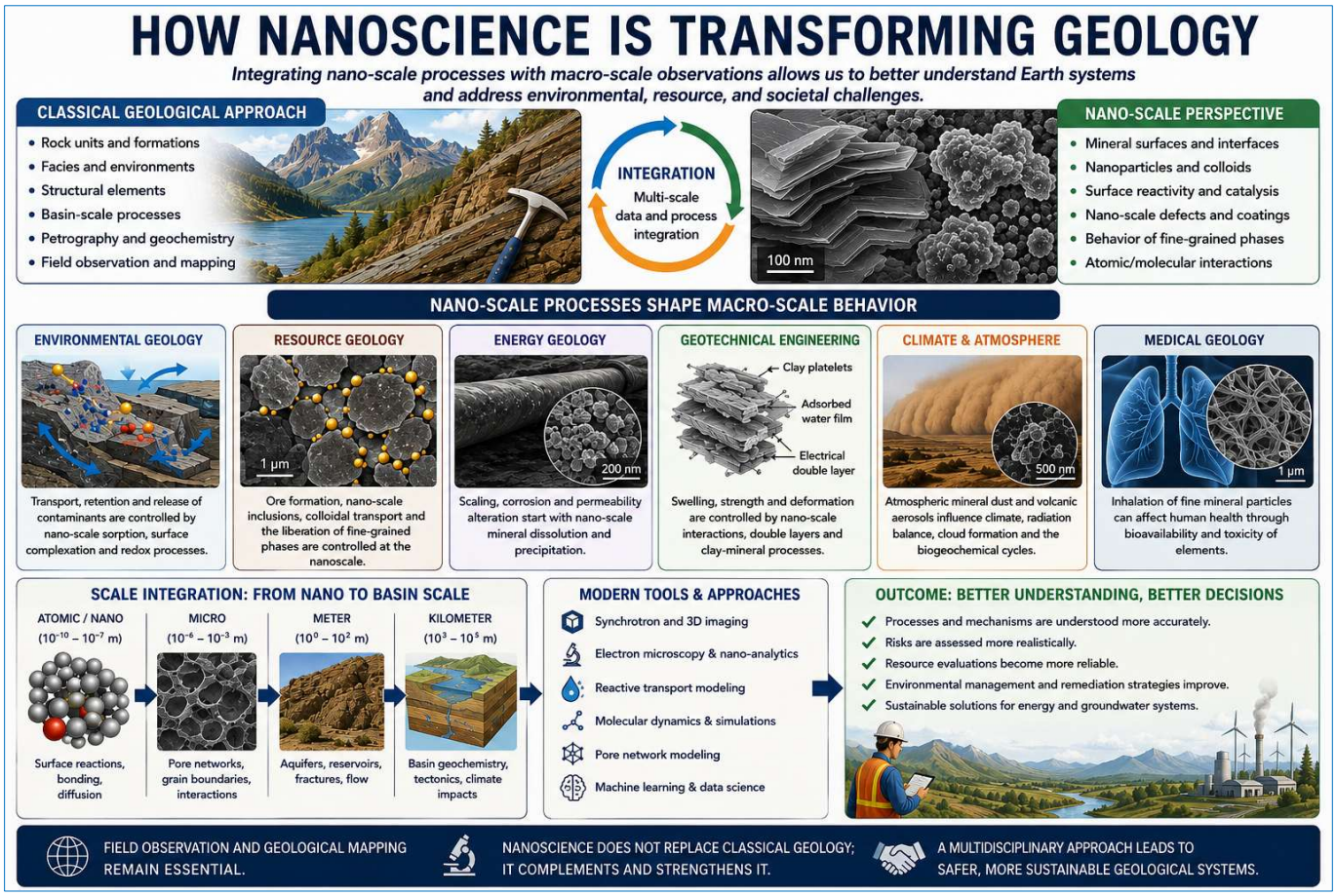

Fig. 17. How nanoscience transforms geological interpretation by connecting field-scale observations with mineral-surface and nanoscale mechanisms (compiled from Hochella et al., 2008; Hochella et al., 2019; Steffen et al., 2015; Gill, 2017)

The next step is to identify the smallest set of measurements capable of falsifying that hypothesis. Mineralogical context should be established before high-resolution analysis so that nanoscale features can be assigned to specific phases and textures. Correlative measurements should then determine whether the feature is common, rare, transient, or localized along preferential pathways. Where possible, nano-observation should be connected to a mass balance or rate measurement (Li et al., 2023; Goodman et al., 2024; Guan and Liu, 2026; Lemelle et al., 2026). This is particularly important for claims involving contaminant removal, metal transport, mineral precipitation, or nanoparticle retention, because images alone cannot establish the magnitude of a flux. The combination of spectroscopy, microscopy, bulk geochemistry, and transport experiments is therefore stronger than any single method, even if the latter has much higher nominal resolution (O'Day, 1999; Hajji et al., 2019; Sit et al., 2021).

Scale transition should finally be tested under boundary conditions that resemble the intended geological setting. A material that performs in deionized water may fail in brine; a reaction measured on powdered minerals may slow dramatically in intact rock; and a colloid that is stable in a

stirred vessel may be filtered at pore throats. Geological decision-making should therefore be based on a hierarchy of evidence: mechanism confirmation, representative matrix testing, core- or column-scale transport, coupled modeling, and field validation (Erfani et al., 2019; Guo et al., 2024; Zwarts and Lesueur, 2024). This evidence ladder, summarized in Table 4, provides a structured framework for translating nanoscale observations into progressively more reliable field-scale geological decisions. The maturity of an application is determined by the weakest link in that chain rather than by the sophistication of the nanoscale characterization.

Table 4. Evidence ladders for translating nanoscale observations to field-scale geological decisions (synthesized from Deng et al., 2022; Zhang et al., 2024; OECD, 2020 and the multiscale framework developed in this review)

Evidence level	Typical evidence	What it can establish	What it cannot establish alone
Mechanism	Surface spectroscopy, AFM, TEM/STEM, molecular or thermodynamic analysis	Existence and plausibility of a nanoscale process	Field relevance or magnitude of impact
Representative matrix	Natural mineral mixtures, site water/brine, realistic temperature and chemistry	Whether the mechanism survives matrix complexity	Spatial reach in a heterogeneous formation
Transport/performance	Columns, intact cores, HP/HT cells, flow-through reactors	Retention, injectivity, kinetics and mass recovery	Reservoir- or aquifer-scale effectiveness
Model integration	Pore-scale and reactive-transport models with uncertainty analysis	Scale coupling and scenario testing	Validity without independent observations
Field validation	Pilot injection, monitoring, tracers, hydraulic and geochemical response	Operational relevance and boundary of applicability	Universal transferability to other geological settings

16. Limits of Current Evidence and Implications for Review Practice

Nanogeoscience is vulnerable to publication and interpretation biases that are common in rapidly developing interdisciplinary fields. Positive laboratory outcomes are more likely to be reported than neutral or unsuccessful trials, particularly for engineered nanomaterials. In addition, the same term - such as nanoparticle stability - may refer to different properties including resistance to aggregation, persistence of primary size, colloidal mobility, or chemical durability (Ju et al., 2017; Dorn et al., 2021; Huggett and Lee, 2024). Cross-study comparison is therefore unsafe unless operational definitions and test media are aligned. Reviews should distinguish mechanistic evidence from application evidence and should not treat a high number of laboratory studies as equivalent to technological maturity (Moni et al., 2019; Woods-Robinson et al., 2024; Li et al., 2026b).

Another limitation is the use of nominal particle size as a surrogate for environmental state. Primary size supplied by a manufacturer or measured in dry powder can differ substantially from hydrodynamic size in formation water, while surface coatings and heteroaggregation with natural colloids may dominate subsequent transport. Dose reporting creates a similar problem: mass concentration, particle number, and reactive surface area can lead to different interpretations of the same experiment (Powers et al., 2007; Caputo et al., 2021; Rueda et al., 2023; Xu et al., 2026). OECD guidance on dispersion and dissolution and ISO terminology provide useful foundations, but geological studies require additional descriptors for pore structure, mineralogy, fluid chemistry, and transformation history (ISO, 2023; OECD, 2020).

Finally, causal attribution becomes difficult when multiple processes operate simultaneously. A permeability change may result from mineral precipitation, particle straining, swelling, gas exsolution, or mechanical deformation. An apparent decrease in dissolved metals may reflect adsorption, precipitation, reduction, or attachment to colloids removed during filtration (Ogata et al., 2018; Su et al., 2025). High-quality studies should therefore include alternative hypotheses and complementary measurements that can discriminate among them. This critical stance does not diminish the importance of nanogeoscience; it makes the field more predictive by separating genuine nanoscale control from coincidental nanoscale observation.

17. Conclusions

Nanoscience has become a necessary scale of inquiry for geosciences because many reactions that control mineral transformation, element transport, fluid behavior, mechanical response, and environmental exposure originate at mineral surfaces, nanophases, or confined pores. Natural nanoparticles and colloids are active components of Earth systems, while engineered nanomaterials offer potentially useful tools whose performance is inseparable from geological context. The most robust applications are those that connect a defined nanoscale mechanism to a measurable field-scale consequence. This includes explaining contaminant retention and colloid-facilitated transport, interpreting nanoscale signatures of ore formation, controlling wettability and injectivity in reservoirs, understanding clay swelling and barrier behavior, managing geothermal scaling, and resolving multiphase processes in subsurface storage. In each case, mineralogy, fluid chemistry, pore structure and transformation history are as important as nominal particle size. The field should therefore move from proof-of-concept nanotechnology toward process-based, multiscale nanogeoscience. Correlative characterization, realistic experimental conditions, reactive-transport modeling, standardized metadata, uncertainty quantification, and field validation are the main requirements for that transition. Such an approach preserves the strengths of classical geology while extending its explanatory power from atomic interfaces to aquifers, reservoirs, ore systems, engineered barriers, and Earth-system processes.

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