

Chemical Weathering and its Impact on Landscape Evolution

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ABSTRACT

The study presents a detailed synthesis of chemical weathering and its deep significance to landscape development. Based on a structured literature review, we examine the key chemical reactions such as solution, carbonation, hydrolysis, and oxidation and the essential environmental parameters, such as climate, lithology, and time, which regulate their rates. Our synthesis demonstrates that chemical weathering is an inherent geomorphic driver of change that results in recognizable landforms including karst landscapes, thick saprolite profiles, etchplains, inselbergs, and spheroidal weathering, and underlies soil development. We highlight the importance of the synergy between chemical and physical weathering in which chemical alteration frequently pre-conditioning rocks for subsequent erosion. Finally, this work emphasizes chemical weathering's critical function in controlling Earth's surface and modulating global biogeochemical cycles, making it relevant to understanding past and future environmental patterns.

Key words: Chemical Weathering, Landscape Evolution, Karst Topography, Saprolite, Soil Formation

INTRODUCTION

The Earth's surface is a dynamic interface, perpetually sculpted by a complex interplay of geological, hydrological, and atmospheric processes. Among these, weathering stands as a fundamental exogenic force, relentlessly transforming solid rock into mobile regolith and dissolved constituents (e.g., Hilton and West, 2020; Bufe et al., 2024). While physical or mechanical weathering fractures rocks into smaller fragments, it is chemical weathering – the decomposition of rocks through chemical reactions – that profoundly alters their mineralogical composition, structure, and ultimately, their susceptibility to erosion and transport (Corentin et al., 2022; Babechuk et al., 2022). This intricate process, driven by interactions between rock, water, and atmospheric gases, operates across vast temporal and spatial scales, from microscopic mineral dissolution within soil pores to the grand-scale shaping of mountain ranges and river basins (Li et al., 2023; Bufe et al., 2024).

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geomorphological driver that radically shapes the development of landscapes (Li et al., 2023; Starke et al., 2020). Weakening rock masses, it predisposes them for later removal by processes like water, wind, and ice, thus contributing to denudation and the formation of varied landforms (e.g., Li et al., 2023; Corentin et al., 2022). The intensity and rate of chemical weathering are controlled by a combination of factors: climate (temperature and precipitation), lithology (mineralogy and rock type), topography (slope and drainage), plant cover, and tectonic activity (Hakim et al., 2021; Li et al., 2023; Bufe et al., 2024). Changes in these controls produce different weathering regimes with specific weathering products and expressions in the landscape. For example, humid tropical settings, with elevated temperatures and copious rainfall, tend to facilitate extreme chemical weathering, resulting in profound saprolite formation and muted topography, although latest research continues to mature our understanding of these climatic controls in various environments (Corentin et al., 2022). In addition to its immediate geomorphological effect on the Earth's surface, chemical weathering has a central role in global biogeochemical cycles, especially for carbon, sulfur, and other nutrient elements (Hilton and West, 2020). The overall uptake of atmospheric carbon dioxide through silicate weathering, for instance, is a vital long-term sink for atmospheric CO₂ that affects the climate on geological timescales (Hilton and West, 2020; Bufe et al., 2024; Parliamentary Office of Science and Technology, 2024). On the other hand, release of dissolved ions into streams adds to the chemical makeup of oceans, influencing marine ecosystems as well as sedimentation (Li et al., 2023). Recent research is also showing that weathering, especially of ancient organic carbon stored in rocks, can serve as a meaningful source of CO₂, refuting earlier assumptions and emphasizing the complexity of the Earth's carbon cycle (Bufe et al., 2024). Knowledge of the complex interplay between chemical weathering and these global cycles is critical to understand past climate evolution and forecast future environmental pathways (Hilton and West, 2020; Bufe et al., 2024). It is the purpose of this manuscript to present a treatise on chemical weathering and its many roles in landscape development. We will discuss the basic mechanisms of chemical rock alteration, examine the most important factors that determine its rates and styles, and explore the various geomorphological expressions generated by its long-term activity. In addition, we will be addressing the general implications of chemical weathering for global biogeochemical cycles and its applicability to today's environmental issues. Through the integration of existing expertise in geomorphology, geochemistry, and Earth system science, this research tries to bring to light the pivotal contribution of chemical weathering in sculpting the planet's surface and controlling Earth's life-supporting systems. This study tries to find out how rocks disintegrate with the passage of time and, in the process, unfurl the mysteries of how our planet's surface is shaped and reshaped. We will also learn about its large effect on Earth's necessary cycles, such as the one that regulates our climate.

METHODOLOGY

This research integrates current knowledge and research regarding the mechanisms of chemical weathering and the observable effects they exert on landscape evolution.

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Because the subject matter spans numerous geological, climatic, and temporal scales, the methodology used is essentially systematic literature review and analytical synthesis technique.

Literature Search and Selection

A comprehensive literature search was conducted across relevant academic databases including, but not limited to, Web of Science, Scopus, Google Scholar, and geological society journals. Keywords used in various combinations included: "chemical weathering," "dissolution," "hydrolysis," "carbonation," "oxidation," "hydration," "landscape evolution," "geomorphology," "karst topography," "soil formation," "saprolite," "inselberg," and "denudation." Emphasis was placed on peer-reviewed articles, books, and authoritative reviews published within the last 50 years. we carefully selected studies that explained the **mechanisms of chemical weathering**, provided **evidence or models connecting weathering to landform development**, discussed the **influence of factors like climate and rock type**, and offered **real-world case studies** to illustrate these principles.

Data Extraction and Thematic Analysis

Relevant information was systematically extracted from the selected literature including **key definitions and conceptual frameworks for understanding** the established terminology and theoretical models for chemical weathering and landscape response, **mechanisms and chemical reactions for detailing** the specific processes (e.g., carbonation of limestone, hydrolysis of silicates) and their associated chemical equations where provided and relevant, of **controlling factors for identification** and categorization of the primary influences on weathering rates (e.g., temperature, precipitation, rock mineralogy, biological activity), **Observing landscape impacts for documenting** specific landforms, features, or broader evolutionary trajectories attributed primarily or significantly to chemical weathering (e.g., karst systems, etchplains, spheroidal weathering, soil profiles), **Quantitative and qualitative relationships for noting** any reported rates of weathering, denudation, or qualitative descriptions of process-form linkages.

A thematic analysis approach was then employed to synthesize the extracted information. This involved identifying recurring themes, common findings, areas of consensus, and points of debate within the literature regarding the efficacy and manifestations of chemical weathering on landscapes.

Conceptual Framework Development

Based on the synthesized literature, a conceptual framework was developed to illustrate the intricate linkages between specific chemical weathering processes, the environmental factors influencing them, and the resulting impacts on landscape morphology and evolution. This framework aims to provide a structured understanding of how the chemical alteration of Earth materials contributes to the diversity of landforms observed globally.

Scope and Limitations

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This review focuses primarily on the fundamental processes of chemical weathering and their macro-scale geomorphic expressions. While acknowledging the crucial interplay, the detailed mechanics of physical/mechanical weathering are only discussed insofar as they facilitate chemical weathering, and vice-versa. The geographic scope encompasses examples from diverse climatic zones to illustrate the varied impacts of chemical weathering under different environmental conditions. Temporal scales discussed range from contemporary process observations to long-term geological evolution.

RESULTS

The comprehensive literature review revealed that chemical weathering is a fundamental and multifaceted geomorphic process, critically influencing landscape evolution across diverse climatic and geological settings. The synthesized findings highlight distinct mechanisms, their controlling factors, and the resultant array of landforms and geomorphic features.

Mechanisms of Chemical Weathering and Their Primary Controls

The literature consistently identifies **solution (dissolution)**, **carbonation**, **hydrolysis**, **oxidation**, and to a lesser extent, **hydration**, as the principal chemical weathering processes. Each process involves specific chemical reactions that alter rock and mineral composition, leading to weakening and breakdown:

Solution/Dissolution is most prominent in highly soluble rocks such as evaporites (e.g., halite, gypsum) and carbonates. Studies show that the rate of dissolution is significantly amplified by the acidity of water, often due to dissolved carbon dioxide forming carbonic acid.

Carbonation, a specific form of dissolution, is widely recognized as the dominant process in **karst landscapes**. Research consistently demonstrates how carbonic acid reacts with calcite in limestone, leading to the removal of material in solution and the development of characteristic surface (e.g., dolines, poljes) and subsurface (e.g., caves, conduits) features.

Hydrolysis, primarily affecting silicate minerals (e.g., feldspars in granites, basalts), is a pervasive process leading to the formation of secondary clay minerals. The literature emphasizes that the intensity of hydrolysis is strongly favored by warm, humid climates and abundant water, playing a crucial role in **saprolite formation** and deeply weathered regoliths.

Oxidation, particularly of iron-bearing minerals, results in the formation of iron oxides (e.g., hematite, goethite), often imparting reddish or yellowish hues to weathered rocks and soils. This process contributes to the weakening of rock structures, making them more susceptible to further physical and chemical breakdown.

Across all mechanisms, the literature consistently identifies climate (temperature and precipitation), lithology (rock and mineral composition), surface area exposure, and time as the paramount controlling factors influencing weathering rates and effectiveness. Warm, humid climates generally accelerate chemical weathering due to enhanced reaction rates and increased water availability. Rocks composed of unstable

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minerals (e.g., olivine, pyroxene, feldspars) or soluble minerals (e.g., calcite, halite) exhibit higher susceptibility.

Direct and Indirect Impacts on Landscape Morphology

Chemical weathering exerts profound impacts on landscape morphology, ranging from the development of highly specialized landforms to the alteration of broader regional topography:

Karst Topography:

The most striking impact is the genesis of karst landscapes through the extensive dissolution of soluble bedrock. Findings show a continuum of features, from small-scale solution pits to large dolines, uvalas, poljes, and integrated subterranean cave systems, directly controlled by the rate and extent of carbonation and solution.

Saprolite and Etchplains:

In tropical and subtropical regions, deep and pervasive chemical weathering, largely driven by hydrolysis, results in the formation of thick saprolite layers (chemically weathered rock retaining original rock texture). Subsequent differential erosion of this regolith frequently leads to the development of etchplains and the exhumation of resistant bedrock remnants as inselbergs or bornhardts.

Spheroidal Weathering: Research consistently attributes the rounding of joint blocks and boulders to spheroidal weathering, where chemical processes (often hydrolysis and oxidation) preferentially attack corners and edges exposed to moisture, leading to concentric exfoliation layers.

Soil Formation and Regolith Development:

Chemical weathering is presented as the foundational process for soil development, breaking down primary minerals into finer particles and secondary minerals (e.g., clays), releasing nutrients, and creating a porous medium essential for biological activity and water infiltration. The depth and composition of regolith are direct outcomes of cumulative chemical alteration.

Slope Stability and Valley Development:

By weakening rock mass strength through mineral alteration and the creation of secondary porosity, chemical weathering significantly preconditions slopes for mass movements. Similarly, the chemical breakdown of bedrock enhances its susceptibility to fluvial erosion, facilitating the deepening and widening of river valleys.

Interplay with other Geomorphic Processes

The literature emphasizes that chemical weathering rarely acts in isolation. It forms a crucial feedback loop with physical weathering, with the latter increasing surface area for chemical attack (e.g., jointing, fracturing), while chemical weathering weakens rock, making it more prone to physical disintegration (e.g., granular disintegration, frost wedging). Furthermore, chemical weathering influences denudation rates by preparing

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material for transport and plays a significant role in long-term global biogeochemical cycles, particularly the carbon cycle, by consuming atmospheric CO₂ during silicate weathering.

DISCUSSION

Our comprehensive review of chemical weathering and its impact on landscape evolution highlights the profound and multifaceted role these processes play in shaping Earth's surface. The results of our literature synthesis clearly demonstrate that chemical weathering isn't just a superficial process; it's a fundamental driver of geomorphic change, often working in tandem with, and preconditioning, physical erosion.

The findings from the literature affirm that the mechanisms of chemical weathering—dissolution, carbonation, hydrolysis, and oxidation, each contribute uniquely to rock breakdown. For instance, the pervasive evidence of karst topography strongly underscores carbonation's critical role, showing how the chemical alteration of limestone can create entire landscapes of caves, sinkholes, and underground rivers. This isn't merely about dissolving rock; it's about the large-scale removal of material that fundamentally reshapes the surface and subsurface. Similarly, the widespread occurrence of saprolite in humid regions, a direct result of hydrolysis, demonstrates how deep chemical alteration can transform solid rock into a weak, soil-like material. This pre-weakening is essential, as it allows subsequent erosion (by water, wind, or gravity) to easily strip away vast quantities of material, leading to distinct landforms like etchplains and inselbergs.

Our synthesis also confirmed the critical influence of environmental factors on weathering rates and effectiveness. Climate, particularly the availability of water and higher temperatures, consistently emerged as a primary control, explaining why chemical weathering is often more intense and leads to more pronounced landforms in tropical and subtropical regions. The type of rock and its mineral composition are equally vital; for example, easily soluble rocks like limestone respond dramatically to chemical attack, while resistant minerals like quartz remain largely unaffected. This differential weathering leads to the diverse patterns we see in landscapes.

Beyond creating specific landforms, the discussion needs to emphasize how chemical weathering interacts with other geomorphic processes. It's rarely an isolated event. Our results showed a strong synergistic relationship with physical weathering: physical forces break rocks into smaller pieces, increasing the surface area, which then accelerates chemical reactions. In turn, chemical weathering weakens the rock, making it more susceptible to physical disintegration and mass movements. This interplay is important for processes such as soil formation, where chemical weathering of bedrock supplies the underlying mineral components that are subsequently further broken down and blended by physical and biological processes. Essentially, our review emphasizes that it's not so much about the chemistry of rocks as it is learning about the very underpinnings of our landscapes. It determines where particular landforms will form, affects slope stability, and lays the ground for the medium of life (soil). Although our approach was to synthesize the current literature, the regular patterns and compelling examples throughout the literature give strong support to these conclusions.

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Furthermore, the long-term implications of chemical weathering extend beyond immediate geomorphic expression to influence global biogeochemical cycles. The dissolution of silicate minerals, for example, consumes atmospheric carbon dioxide over geological timescales, acting as a crucial negative feedback on Earth's climate system (Berner, 2004). Conversely, the release of dissolved ions from weathering rocks contributes significantly to ocean chemistry and nutrient cycling, impacting marine productivity and the global carbon budget (Gaillardet et al., 1999). This intricate coupling between surficial processes and global cycles underscores the profound Earth system implications of chemical weathering, highlighting its role as a fundamental control on both landscape evolution and planetary habitability.

The role of biological activity also warrants further emphasis in the context of chemical weathering. While physical and chemical processes are often discussed, biological agents, from microorganisms to plant roots, significantly enhance weathering rates (Taylor & Blum, 1995). Lichens and bacteria produce organic acids that chelate metal ions, accelerating mineral dissolution, while plant roots physically penetrate cracks and release organic compounds that promote chemical breakdown. This bio-geomorphic feedback loop is particularly pronounced in vegetated landscapes, where the continuous interaction between life and lithosphere creates unique weathering profiles and contributes to the distinctive character of biotically active terrains.

Finally, a comprehensive understanding of chemical weathering has critical practical implications for human societies. The formation of saprolite, for instance, while a natural process, can significantly reduce slope stability, increasing the risk of landslides and debris flows in susceptible regions, particularly under changing climatic conditions (Montgomery & Brandon, 2002). Moreover, chemical weathering controls the availability of essential nutrients in soils, directly impacting agricultural productivity and ecosystem health. Knowledge of these processes is therefore vital for sustainable land management, natural hazard assessment, and predicting the long-term impacts of environmental change on Earth's critical zone.

This discussion finally supports that chemical weathering is a dynamic and integral part of the Earth's geomorphic engine, continually molding and remolding the surface we live on.

CONCLUSION

The study has investigated and elucidated the complex interaction between chemical weathering and landscape development systematically, based on a thorough review of the available scientific literature. The results clearly confirm that chemical weathering is more than a secondary process but an integral and ubiquitous force that shapes Earth's surface in various environments and on multiple timescales. Our analysis supports that separate chemical processes viz. dissolution, carbonation, hydrolysis, and oxidation, uniquely and all together propel the disintegration of rocks and minerals. The processes, markedly controlled by controlling factors like climate, lithology, and time, produce a broad range of observable geomorphic characteristics. Some of the key effects are the creation of distinctive karst landscapes, the genesis of very deep saprolite profiles giving rise to landforms such as etchplains and inselbergs, the typical rounding that occurs through spheroidal weathering, and

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importantly, the initial establishment of soil profiles and regolith. In addition, this review emphasizes the fundamental interaction of chemical weathering with other geomorphic processes. Chemical change often conditions bedrock to make it more prone to physical erosion, mass wasting, and fluvial transport. This synergistic interaction highlights the integral approach of landscape evolution, wherein the chemical alteration of Earth materials serves as an essential precursor and initiator of subsequent physical change and denudation. Overall, chemical weathering is a vital part of the Earth's geomorphic system. Its steady operation controls long-term relief development, drives landform stability, and is a critical factor in the cycling of nutrients as well as the larger interaction between the biosphere and lithosphere. A thorough understanding of these chemical processes is therefore paramount for comprehending the dynamics and diversity of our planet's landscapes.

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