LA SACRA ALCHIMIA

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LA SACRA ALCHIMIA
Processi chimici, contaminanti naturali e antropici
e implicazioni per gli ecosistemi e la salute umana

Tra roccia, acqua e aria, l'alchimia degli elementi decide il confine sottile tra risorsa e rischio.

La collana «La sacra alchimia» ospita volumi dedicati alle trasformazioni dei componenti inorganici e organici nell'ambiente e alle loro ricadute sulla salute umana. L'obiettivo è integrare geochimica ambientale, idrogeochimica, scienze del suolo, tossicologia, epidemiologia ambientale e scienze dei materiali, con particolare attenzione a contaminanti naturali e antropici, scenari di esposizione e valutazione del rischio. La collana accoglie manuali avanzati, monografie tematiche e casi studio che combinano monitoraggio, modellistica, tecniche analitiche d'avanguardia e approcci interdisciplinari per supportare la gestione sostenibile delle risorse, la mitigazione degli impatti e le politiche di tutela degli ecosistemi e delle comunità esposte.

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ENVIRONMENTAL GEOCHEMISTRY AND HEALTH

THEORY, METHODS AND APPLICATIONS

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To Janeth,
my wife, my friend, my companion in life

SUMMARY

PREFACE

The present volume, Environmental Geochemistry and Health, was conceived in response to the urgent need for a deeper understanding of the intricate relationships between geochemical processes and their implications for ecosystems and human well-being. In recent decades, the intensification of anthropogenic pressures, including mining activities, industrial emissions, and the widespread use of agrochemicals, has led to the mobilisation and redistribution of potentially toxic elements (PTEs) within the environment, often with poorly understood consequences for health.

Environmental geochemistry, a discipline at the intersection of Earth sciences, chemistry, toxicology, and environmental health, provides essential tools to investigate the sources, mobility, and fate of natural and anthropogenic contaminants. Yet, despite its critical relevance, a comprehensive, integrative text that bridges geochemical theory with real-world health outcomes has remained elusive, especially in educational contexts. This book aims to fill that gap.

Drawing on recent scientific advances and case studies from diverse environmental settings, the book adopts a multidisciplinary approach to characterising contaminated sites, tracing pollutants using isotopic and elemental signatures, and understanding biogeochemical cycles perturbed by human activities. Particular attention is paid to risk assessment methodologies, remediation strategies, and decision-support tools, which are vital for evidence-based environmental management and policy.

The structure of the book is designed to support both didactic progression and thematic depth. It is suitable for advanced undergraduate and graduate students, environmental scientists, geochemists, engineers, public health professionals, and decision-makers working at the science-policy interface. The chapters are enriched with conceptual figures, comparative tables, and real-world datasets to facilitate learning and application.

Ultimately, this work reflects a vision of geochemistry not merely as a descriptive science, but as a proactive discipline, capable of contributing to sustainable development, environmental justice, and planetary health.

INTRODUCTION

Environmental geochemistry stands at the convergence of geosciences, chemistry, and public health, representing a powerful discipline that deciphers the chemical dynamics of the Earth's surface and their repercussions on living organisms. It addresses the sources, transformations, transport mechanisms, and ultimate fate of chemical species-both naturally occurring and anthropogenically introduced-across interconnected environmental compartments: rocks, soils, waters, sediments, and the biosphere. As societies increasingly grapple with environmental degradation, pollution, and associated health crises, environmental geochemistry emerges not only as a diagnostic science but as a critical predictive and preventative tool.

The roots of geochemistry trace back to the early 20th century, initially oriented toward understanding the distribution of elements in the Earth's crust and their role in petrogenesis. With the advent of modern analytical techniques and the growth of environmental awareness in the post-industrial era, geochemistry underwent a paradigm shift. The rise of environmental geochemistry in the 1970s and 1980s reflected growing concern about the ecological and health impacts of trace element pollution, acid mine drainage, radioactive waste disposal, and industrial emissions.

Today, environmental geochemistry is a fully interdisciplinary science. It draws on analytical chemistry, mineralogy, hydrogeology, soil science, ecology, and toxicology to elucidate how chemical elements move through the environment and how they can adversely affect human health, especially in vulnerable populations and ecosystems. Unlike classical geochemistry, which often focuses on inert or long-term geological processes, environmental geochemistry emphasizes contemporary dynamics, biogeochemical interactions, and anthropogenic perturbations to natural cycles.

All life is built upon the availability and cycling of chemical elements. Elements such as carbon (C), nitrogen (N), phosphorus (P), iron (Fe), and zinc (Zn) are essential for metabolic functions. However, the boundary between essentiality and toxicity is narrow, concentration-dependent, and influenced by factors such as chemical speciation, bioavailability, and environmental context.

Some elements, arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb), have no known biological role and are toxic even at trace levels. Others, like chromium (Cr), manganese (Mn), and selenium (Se), can be both essential and harmful depending on dose and oxidation state. The geochemical behavior of these elements-how they are mobilized, transported, adsorbed, and transformed-is central to understanding exposure risk and toxicological outcomes.

A key challenge in environmental geochemistry is distinguishing between geogenic and anthropogenic sources of contamination. Geogenic processes, such as weathering of metalliferous rocks, hydrothermal activity, and volcanic emissions, can release significant amounts of toxic elements into the environment. Naturally elevated arsenic concentrations in groundwater aquifers of South Asia, fluoride in volcanic regions, or uranium in sedimentary basins are examples of purely natural but hazardous geochemical contexts.

Conversely, human activities have drastically amplified elemental fluxes in the environment. Industrial discharges, mining operations, fossil fuel combustion, agricultural practices, and waste mismanagement have led to the accumulation of toxic substances in soils, sediments, and aquatic systems. In many cases, anthropogenic mobilization exceeds natural geochemical baselines by orders of magnitude.

Moreover, climate change and land-use alteration further complicate contaminant transport by modifying redox conditions, hydrological regimes, and sediment dynamics.

Environmental geochemistry plays a pivotal role in elucidating the pathways by which toxic substances reach human populations.

These pathways include:

- Direct ingestion of contaminated water (e.g., arsenic-laden groundwater);
- Consumption of polluted food (e.g., cadmium in rice, mercury in fish);
- Inhalation of airborne particles (e.g., lead in urban dust);
- Dermal contact with contaminated soils or industrial residues.

Each exposure route is governed by the complex interplay between geochemical speciation, environmental media properties (e.g., pH, redox potential, organic matter), and human behavior. Critically, not all chemical species of a given element are equally toxic. For instance, Cr(VI) is far more hazardous than Cr(III), and the methylated form of mercury (MeHg) is far more bioavailable than its inorganic counterpart.

Geochemical methods are indispensable in environmental risk assessment. They enable the determination of background values, the mapping of contamination plumes, the identification of pollutant sources (e.g., through isotopic or statistical fingerprinting), and the estimation of contaminant mobility and bioaccessibility.

Advanced tools such as sequential extraction, geochemical modelling (e.g., PHREEQC, Visual MINTEQ), and speciation analysis provide insights into the partitioning of elements among solid, liquid, and gaseous phases. Coupled with epidemiological and toxicological data, these insights allow for more accurate assessments of human health risk and the design of appropriate mitigation strategies.

Importantly, the integration of geochemical and biomedical knowledge facilitates the transition from mere contamination studies to proactive environmental health science, identifying not just the presence of a contaminant, but its potential to cause disease under realistic exposure scenarios.

This book draws on a wide range of international case studies to illustrate the application of environmental geochemistry to real-world problems. From the acidification of mining regions in the Andes, to arsenic contamination in Bangladesh and India, from lead exposure in urban environments to mercury accumulation in Amazonian aquatic food webs-each case highlights unique combinations of geochemical conditions, socio-economic pressures, and health outcomes.

These case studies also serve to underline the disparities in monitoring capabilities, remediation technologies, and public health infrastructures across the globe. The burden of exposure is disproportionately borne by populations in low-income regions, often without access to safe water, effective regulation, or technical expertise.

Environmental geochemistry cannot operate in isolation. To effectively tackle complex environmental health challenges, it must intersect with disciplines such as medical geology, toxicology, epidemiology, environmental policy, and risk communication. A successful environmental geochemist must be as comfortable discussing sorption isotherms and redox buffering as understanding regulatory frameworks and public engagement.

The emergence of "One Health" paradigms and planetary health frameworks further strengthens the relevance of geochemistry in transdisciplinary dialogues. These approaches recognize the interconnectedness of human, animal, and environmental health, and position geochemistry as a foundational science in understanding shared vulnerabilities.

This volume is designed to guide readers-from students to researchers, consultants, and policymakers-through the theoretical principles and practical applications of environmental geochemistry in the context of health.

The health of our planet and its inhabitants is increasingly shaped by chemical interactions at the Earth's surface. Environmental geochemistry offers not only a lens through which to diagnose problems but also the tools to anticipate and mitigate them. As we move deeper into the Anthropocene, where natural systems are reconfigured by human activity, the integration of geochemistry and health science becomes not merely important, but imperative.

By bridging the knowledge gap between Earth science and life science, this book aspires to contribute to that mission-fostering a scientifically informed and health-conscious approach to managing the geochemical challenges of our time.

FOUNDATIONS OF ENVIRONMENTAL GEOCHEMISTRY

Definition and Relevance of Environmental Geochemistry

Environmental geochemistry is the scientific discipline that investigates the abundance, distribution, mobility, and chemical transformations of elements and compounds within the Earth's surficial environments, namely soils, sediments, surface and groundwater, biota, and the atmosphere. It encompasses both natural (geogenic) and anthropogenic (human-induced) processes that shape the chemical composition of these compartments and the complex interactions occurring at their interfaces. By tracing these processes, environmental geochemistry serves as a powerful interpretive framework for understanding the environmental behaviour of chemical species and their implications for ecosystem functioning and human health.

At its core, environmental geochemistry derives from classical geochemistry, but it transcends disciplinary boundaries by integrating concepts and methodologies from environmental science, analytical chemistry, geology, hydrology, soil science, mineralogy, microbiology, toxicology, and public health. This interdisciplinarity is essential to comprehensively assess the sources, transport pathways, transformation mechanisms, and sinks of chemical elements, particularly potentially toxic elements (PTEs) and emerging contaminants, within dynamic environmental systems.

The relevance of environmental geochemistry has grown markedly in recent decades in response to intensifying anthropogenic pressures such as mining, industrialisation, urban sprawl, waste mismanagement, fossil fuel combustion, and agricultural intensification. These activities have disrupted the natural geochemical balance, leading to the remobilisation and bioaccumulation of trace elements and compounds that can be harmful even at low concentrations. Arsenic contamination in groundwater, mercury accumulation in aquatic food webs, cadmium enrichment in agricultural soils, and the proliferation of acid mine drainage in post-mining landscapes are just a few emblematic examples of geochemical issues with serious environmental and public health consequences.

Beyond describing spatial and temporal patterns of elemental distribution, environmental geochemistry focuses on key mechanistic aspects such as speciation (i.e. the chemical forms of elements), reactivity (including redox and sorption processes), bioavailability (the extent to which contaminants are accessible to organisms), and toxicity thresholds. These factors determine the environmental fate and ecological risks of contaminants far more than total concentrations alone.

From a practical standpoint, environmental geochemistry underpins many applied domains, including:

- Risk assessment and the delineation of contaminated sites;
- Remediation planning, through geochemical modeling and monitoring of natural attenuation;
- Public health protection, by identifying exposure pathways (e.g. drinking water, crops, inhalation of dust);
- Environmental forensics, aimed at source identification and pollutant fingerprinting;
- Policy development, offering scientifically sound data to inform environmental regulations and sustainable land use.

The discipline also plays a central role in advancing concepts such as geochemical baselines, environmental standards, and critical loads,