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Discussion

The geological footprint of plastics

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ABSTRACT

The significant impact of plastics on Earth's environments has transformed from being a symbol of modern innovation to a major ecological concern. This perspective paper explores the integration of plastics into geological contexts, emphasizing their role in contemporary sedimentary processes. It examines the lifecycle of plastics, from production to disposal, and their subsequent interaction with natural sedimentary cycles. The production and usage of plastics have led to considerable environmental repercussions. One of these, is their incorporation into geological systems and the formation of novel geological materials. Such a phenomenon challenges traditional geological concepts and necessitates a multidisciplinary approach encompassing geology, chemistry, and environmental science.

Invented in 1907, plastics have significantly impacted society, initially symbolizing modernity but now posing major environmental concerns due to their enduring presence (Williams and Rangel-Buitrago, 2022). Their remarkable properties have made them indispensable in daily life; however, their pervasive production, use, mismanagement, and accumulation presents significant environmental and societal challenges.

Comparing the properties of sediments and plastics offers insights into their roles and impacts within geological contexts. Sediments, formed from natural rock weathering, reflect specific environmental conditions, and transport history and have characteristics like porosity and permeability (Rangel-Buitrago and Neal, 2023). Plastics, composed of long-chain hydrocarbon polymers, show diverse textures and morphologies altered by environmental degradation, often contrasting with sedimentary particles in buoyancy, sorting, and fabric (Andrady, 2022). While sediments have a range of densities and sorting characteristics indicative of natural processes, plastics' behaviors and ecological impacts vary due to their manufacturing processes and buoyancy (UNEP, 2021).

The environmental impact of plastics, especially through their lifecycle, has become a critical concern (Williams and Rangel-Buitrago, 2022). This lifecycle starts with extracting crude oil or natural gas to mainly produce polyethylene terephthalate (PET), a process reliant on fossil fuels with significant environmental costs (UNEP, 2021). Transporting these raw materials to refineries, fraught with risks like spills and accidents, often suffers from inadequate regulation, leading to safety and environmental issues. The refining and production stages transform materials into plastic resins, generating air pollution and toxic emissions (Rangel-Buitrago et al., 2022). PET resin production significantly contributes to CO2 emissions. Even the distribution phase contributes to environmental degradation, especially through CO2 emissions and potential plastic losses in transit. The total volume in plastic production and consumption, over 9.2 billion tons since 1950, with a significant rise expected, reflects its widespread use, particularly in packaging, textiles, and consumer products. Major consumers include North American countries, China, India, and Western Europe (UNEP, 2021).

The concept of cycling is key to understanding the transformation and persistence of substances in Earth's system, including sedimentary and plastic cycles (Rangel-Buitrago and Neal, 2023). The sedimentary cycle, spanning geological timescales, involves sediments' formation, transport, and transformation into rocks, contrasting with the much shorter, human-driven plastic lifecycle from production to disposal.

Plastics' high prevalence in the environment links them inextricably with the cycle of sedimentary rocks. This intersection occurs when plastics are discarded and enter the environment uncontrolledly, beginning their integration into the geological cycle. Once in the environment, plastics are subject to physical and chemical processes like

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those affecting sediments, transforming, and moving them through various environments. This integration allows plastics to be incorporated into the geological cycle, not just as a transient contaminant but as a persistent component capable of leaving a lasting imprint in the geological record, reflecting anthropogenic influence (Waters and Turner, 2022).

The environmental impacts of plastics persist well beyond their disposal, highlighting significant challenges in their lifecycle. Despite ongoing recycling efforts, the complexity and economic challenges associated with the process often make it unfeasible, thereby exacerbating the issue of plastic pollution across various Earth environments. Global plastic production is anticipated to surge to 550 million tons by 2026. Coupled with inefficient waste management practices, this increase has led to a situation where 91 % of plastics are not recycled (Williams and Rangel-Buitrago, 2022). Consequently, 35 % of discarded plastics end up contaminating natural ecosystems, especially marine environments (UNEP, 2021). Each year, at least 14 million tons of plastics are deposited into the oceans, significantly threatening marine biodiversity and ecosystems. This escalating crisis is further highlighted by projections suggesting that by 2050, the mass of plastics in our oceans could surpass the total biomass of fish (Lebreton and Andrady, 2019).

Approximately 86 % of improperly managed plastic has the potential to integrate into the geological record, undergoing weathering and degradation processes akin to those affecting rocks and minerals (UNEP, 2021; Rangel-Buitrago et al., 2022). Weathering of sediments involves the natural breakdown of materials through physical, chemical, and biological interactions (Rangel-Buitrago and Neal, 2023), while plastic degradation occurs through factors like sunlight exposure, temperature, and biological activities (Andrady, 2022). These processes result in the erosion and fragmentation of materials, shaping landscapes and producing smaller plastic particles, including microplastics. The interaction between these processes is notable, especially in coastal areas where they can simultaneously occur. Environmental conditions such as sunlight exposure, temperature variations, and mechanical forces significantly influence the rate and extent of plastic degradation, with varying effects observed in different zones, from beaches to the ocean surface and the bottom sediment environment (Rangel-Buitrago et al., 2022).

The transport of sedimentary and plastic particles in aquatic environments is dictated by a complex combination of gravitational forces and hydrodynamic processes. Natural sediment transport, a cyclical process, is influenced by characteristics such as particle size and density. This natural transport plays a critical role in shaping aquatic landscapes and influencing ecological cycles. In contrast, plastics add a layer of complexity due to their variable density, buoyancy, and size, which significantly affect their transport dynamics (van Sebille et al., 2020). The differences between sediments and plastics are evident in the mechanisms of transport, including advection, turbulent diffusion, wave-induced motion, and resuspension. Each of these processes plays a distinct role in determining the distribution and behavior of these materials in water bodies (van Sebille et al., 2020).

Buoyancy directly affects the transport pathways of plastics. Buoyant plastics tend to remain afloat, carried by surface currents and winds, enabling them to travel vast distances across ocean basins. In contrast, denser plastic materials, with buoyancy closer to or less than that of water, are more likely to sink and be transported by bottom currents or remain in relatively confined areas, depending on local hydrodynamics (van Sebille et al., 2020). This variation in buoyancy leads to different spatial distribution patterns, influencing where these plastics can accumulate and the likelihood of interaction with diverse organisms. Particularly, buoyant plastic particles are prone to extensive transport across vast distances and over prolonged periods, unlike sediment particles, which typically follow shorter and more predictable trajectories.

The dispersion and accumulation of plastics are significantly influenced by physical processes such as wind, wave, and current dynamics. Earth environments, varying from high-energy to low energy, dictate the fragmentation, suspension, and transport patterns of plastic debris, with larger and denser particles tending to settle more rapidly. Once in the sediment, plastics can be buried, temporarily reducing their ecological impact, but posing long-term environmental threats if resuspended. Sediment characteristics, including grain size and organic content, along with hydrodynamic conditions like wave energy and tidal dynamics, play crucial roles in the interaction between plastics and sediments (Rangel-Buitrago et al., 2022). Extreme weather events, as well as human-induced changes such as urbanization, further influence these interactions.

Plastics are increasingly becoming a part of sedimentary rock formation through a process akin to diagenesis (processes that transform sediments into sedimentary rock), undergoing physical and chemical transformations in various environments such as beaches and deltas. This process results in the integration of plastic waste with natural materials like sand and organic debris, forming new types of rock (Rangel-Buitrago and Neal, 2023; Rangel-Buitrago et al., 2022). Unlike traditional sedimentary rock diagenesis, which is a natural, geological process occurring over millennia, the diagenesis of plastic-derived rocks is a recent phenomenon, heavily influenced by human activities and environmental conditions. These newly formed rocks, varying in durability and composition, highlight the significant impact of human activity on the environment, and present an emerging area of study with far-reaching ecological implications. The formation of these rocks is dependent on factors such as the type of plastic, environmental conditions like temperature and UV exposure, and physical forces like wave action.

In contemporary geology, the traditional definition of rocks as aggregates of inorganic, crystalline minerals are evolving due to the prevalent integration of plastics into the environment, leading to the formation of new rock types. Traditionally classified as igneous, sedimentary, and metamorphic, rocks now increasingly include plastics in their composition, raising questions about their classification. Rock formed with plastics, primarily akin to sedimentary rocks, originate from the weathering of both rocks and plastics, followed by transport and deposition by natural agents. These processes lead to three distinct new rock types: Detriplastic Rocks, consisting of plastics mixed with weathered rock particles (Fig. 1); Bioplastic Rocks, where plastics combine with organic materials; and Chemiplastic Rocks, formed through chemical precipitation processes involving plastics (Rangel-Buitrago and Neal, 2023; Rangel-Buitrago et al., 2022).

The formation of these plastic-derived rocks, represents a novel geological phenomenon with an indeterminate timeframe that could range from decades to centuries, influenced by environmental conditions, the type of plastics involved (each plastic has a defined age of creation), and the geological processes at play. Different plastics vary in chemical composition, density, and degradation resistance; for example, PET and HDPE are more durable than PS, making them more likely to be incorporated into rock formations. Environmental conditions such as higher temperatures and UV exposure accelerate plastic degradation, breaking them into smaller particles that mix with natural sediments. This process is aided by physical forces like wave action, which breaks down and mixes plastic particles with sediments along shores, and other mechanical forces such as compression, shearing, and abrasion by sediments. These factors collectively facilitate the integration of plastics into sedimentary structures and their lithification into new rock types.

Bioplastic Rocks, consisting of plastics intermixed with organic materials, are validated using petrographic analysis, scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy to determine their composition. Chemiplastic Rocks, on the other hand, emerge from chemical precipitation processes involving plastics and are validated through geochemical assays, X-ray diffraction (XRD), and X-ray fluorescence (XRF) to confirm the presence of transformed polymers and the rock's mineralogical characteristics.

Additionally, there are a set of elements formed by the interaction of plastics with natural environments. These include Pyroplastics (Fig. 1), amorphous matrices formed from burnt plastics, notable for their

Fig. 1. This figure presents a comprehensive overview of various rock types and soils influenced by synthetic materials. It includes: Detriplastic Rock (Plastiglomerate): Displayed both as a general view and in a thin section, this rock type features plastics (Pl) as the binding matrix, integrating naturally occurring quartz grains (Qz). The plastiglomerate exemplifies how synthetic materials can embed within and stabilize natural sedimentary particles, offering a vivid representation of anthropogenic influence on geological formations. Pyroplastics: This sample showcases amorphous plastic matrices that encapsulate angular to weathered, rounded clasts. These formations result from plastics exposed to high temperatures and chemical weathering, highlighting the transformation of synthetic materials under environmental stress and their subsequent integration into the geological cycle. Anthrosol: This anthropogenic soil is composed of a mixture of urban detritus, including glass, plastics, and rubber, combined with reworked sedimentary fill. The depicted Anthrosol originates from urbanization efforts in the 1980s and serves as an example of how human activities modify soil profiles, particularly in urban settings.

positive buoyancy in seawater (Turner et al., 2019). Plasticrusts consist of plastics embedded in porous rocks, influenced by oceanic forces (Ehlers and Ellrich, 2020). Plastitar is a blend of tar and microplastics attached to rock surfaces (Dominguez-Hernandez et al., 2022). Biofouled plastics are plastics colonized by various aquatic organisms, highlighting the biofouling process (Ehlers and Ellrich, 2020). Lastly, Plasticlasts are remnants of weathered and eroded plastics, such as pyroplastics (Avelar et al., 2022).

Plastics serve as crucial indicators for interpreting human behavior, effectively acting as modern-day 'fossils' or more accurately, "artifacts". These artifacts, encompassing both Technofossils and urban fossils, provide insights into human interaction with plastics, from their origin to the present state. Technofossils, including a wide range of manufactured items from early human tools to current plastic objects, illustrate the evolution of human technology (Zalasiewicz et al., 2014). Urban fossils, mainly plastics embedded in urban materials like asphalt and concrete, offer traces of human activities in urban environments (Cirilli and Delfino, 2016). Together, these modern artifacts not only serve as indicators of recent periods, correlating rocks and sediments of similar ages but also highlight the significant impact of human activities on the environment, marking a distinct footprint in the geological record of the Anthropocene era.

Anthrosols and Plastisols represent unique, entirely human-created soil types. Anthrosols consist of various litter items, including glass, plastics, and rubber, while Plastisols are composed exclusively of plastics (Rangel-Buitrago and Neal, 2023; Rangel-Buitrago et al., 2022). These layers of litter-derived soil can intermix with the O Horizon (rich in organic matter) and the A Horizon (containing mineral matter and humus) within soil profiles. These human-made layers are particularly significant because they contain materials that can be dated, offering relative dating information. This allows for the determination of the age of layers situated above (which are younger than the litter items) and below (which are older than the litter items).

The type of plastic and its chemical composition crucially impact the formation of plastic-derived rocks and plastisols, as well as their role as stratigraphic markers of the Anthropocene. Various plastics, depending on their polymer structures and additives like plasticizers or UV stabilizers, degrade at differing rates and interact uniquely with natural sediments and environmental agents, influencing how they integrate into sedimentary processes. For example, durable plastics such as PET and HDPE are more likely to form 'detriplastic' rocks, acting as a binding matrix for sediment particles, whereas more brittle plastics like polystyrene tend to break down into microplastics, contributing to plastisol formation.

The utilization of plastics as stratigraphic markers has become a pivotal indicator of anthropogenic impacts (Zalasiewicz et al., 2019). Plastics, distinguished by their unique texture, composition, size, color, shape, sorting, fabric, and structure, serve as definitive markers of the Anthropocene epoch. Plastics, embedded within sediments, reveal significant insights into the energy conditions, depositional processes, and historical context of these environments. Advanced techniques like Fourier-transform infrared and Raman spectroscopy facilitate the analysis of plastic characteristics, age, and distribution, linking their emergence to the mid-20th century's surge in mass production. This correlation highlights the profound impact of human activity on geological formations. The presence of plastics in sediment layers not only marks a distinct phase in Earth's geological history but also underscores the pressing environmental challenges and the need for conscientious stewardship in this era.

The presence of plastics within geological formations marks a significant transformation in the field of geology, presenting challenges to conventional classifications and emphasizing the need for a multidisciplinary approach that encompasses geology, chemistry, and environmental sciences. This integration of synthetic materials into the Earth's stratigraphy not only has environmental implications, affecting sedimentary dynamics and soil integrity, but also acts as a distinct stratigraphic indicator of the Anthropocene epoch. It reflects on human technological advancements and societal values. Moreover, the incorporation of plastics into geological layers carries profound implications for industries such as mining and construction, compelling the adoption of comprehensive and sustainable operational practices. At this pivotal moment in geological history, where human impact is becoming increasingly evident, there is a critical need for collaborative research endeavors. These efforts should focus on reducing environmental impacts and unlocking new scientific opportunities, thereby addressing the urgent challenges posed by the integration of synthetic materials into natural systems.

CRediT authorship contribution statement

Nelson Rangel-Buitrago: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Francois Galgani:** Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **William J. Neal:** Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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