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Research Article

Classification Framework for Assessing Anthropogenic Sedimentary Facies

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As the mass of human-made materials now surpasses that of Earth's total dry biomass, there is a critical need for sedimentologists to account for anthropogenic materials when analyzing depositional environments. To address this, a classification scheme is presented that extends traditional sedimentological models to encompass the diversity of modern sediments and their complex dynamics. Through relying on established sedimentological principles, the framework incorporates bed-scale, grain-scale, and sedimentary structure descriptors, as well as a methodology for describing the composition of a deposit and flexible nomenclature. It is designed to be integrative and adaptable, permitting the incorporation of additional descriptions as necessary, and is applicable across depositional settings that are dominated by either natural or anthropogenic processes. The scheme offers a practical, systematic approach to categorize and analyze the textures and structures of anthropogenic sediments, facilitating the reconstruction of modern and geologically recent environments. This unifying starting point enables more detailed predictions of material behavior and their environmental impacts, with implications for recycling, reuse, and management strategies. Furthermore, standardized nomenclature will enhance the capacity for data comparability across field sites, facilitating further understanding of our environment. Applications of this classification scheme include many interdisciplinary possibilities, overlapping with archeology, environmental monitoring, and engineering. By adopting this classification, sedimentologists can forge a deeper understanding of the stratigraphic record of the Anthropocene, contribute to developing more comprehensive strategies to manage Earth's changing landscapes, and better understand our future geological record.

INTRODUCTION & BACKGROUND

Today's Earth has a host of sedimentary material that is geologically novel in composition and distribution, such as metal, plastic, glass, artificial aggregates, and many others, which, due to their abundance and durability, will form lithostratigraphic indicators as part of our future geological record (Corcoran et al., 2014; Ford et al., 2014; Zalasiewicz et al., 2014, 2016). In 2020 the collective mass of human-made materials surpassed that of Earth's total dry biomass (Elhacham et al., 2020), which suggests that a significant portion of the sedimentological record being formed today could comprise anthropogenic materials. Yet, the investigation into the lateral and vertical distributions of anthropogenic materials by sedimentologists remains incomplete. Recognizing these incredibly varied materials as a permanent fixture of the sedimentary sphere rather than as simply contamination and pollution has become crucial for understanding the processes and dynamics of contemporary Earth. There are studies of anthropogenic lithostratigraphy (Ford et al., 2014), and an introduction of terminologies surrounding technofossils (i.e., human-made geological evidence), (Zalasiewicz et al., 2014), and the technosphere (i.e., the global anthropogenic technological system) (Zalasiewicz et al., 2017), yet we lack a framework for a fundamental sedimentological descriptive and interpretive understanding of anthropogenic deposits.

Archaeologists generally consider anthropogenic materials as "artifacts", which can aid in understanding the context of historical human societies (Renfrew & Bahn, 2014), yet the sediment surrounding the artifacts is not always studied. Soil scientists generally consider anthropogenic items as clasts under the Food and Agriculture Organization of the United Nations (2006) guidelines, which do not

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specifically address the classification of anthropogenic materials or contaminants in soil and sediment. Weber (2022) developed the framework to add plastic as a stand-alone component, however, the additions and guidelines for the properties to assess remain most suited to soil science (such as a scale of fixation), and only plastic is delineated by the scheme. Engineering geologists use the terms "anthropogenic fill", "made ground", and "artificial ground" to highlight where natural geologic deposits have been significantly altered or replaced by human activity (British Standards Institution, 2015), which is adequate for engineering geological purposes, but as redevelopment of brownfield sites becomes more common, a method for more comprehensive analysis may become increasingly important. Environmental sampling is undertaken on many materials and chemicals alike, and when plastic is studied in sediment, the focus is primarily on quantifying its mass, form, and composition (Tramoy et al., 2020), from fluvial environments (e.g., Hurley et al., 2018) to deep water environments (e.g. Kane et al., 2020), thereby improving our understanding of their dispersion and associated hotspots. As such, we see that these current frameworks, from archaeology to engineering geology, tackle human-made materials under specialized focus, such that they cannot form a unified sedimentological perspective. This disciplinary fragmentation underscores an urgent need for an integrated classification scheme that can capture the full spectrum of anthropogenic impacts on sedimentary environments. The potential of sedimentology to further enhance this understanding of material distributions and legacies is substantial, and relies on the development of a robust classification framework.

The strength of the framework for traditional sedimentology lies in its systematic approach to categorize and analyze sedimentary structures and textures, which enables us to reconstruct past and present processes and environmental conditions, as well as make predictions (Reading et al., 1996). Its well-established universal principles, such as facies analysis and Walther's Law (Middleton, 1973), provide a solid foundation for interpreting the stratigraphic record and understanding Earth's environmental evolution. Contemporary facies cannot be adequately described by existing methodologies in the literature because traditional sedimentary models, techniques, and classifications do not encompass the diversity of the modern, anthropogenically influenced environment. All sedimentary studies must begin with the categorization and quantification of the sedimentary deposits themselves such that lateral, vertical, and temporal trends and changes may be recorded, enabling the transport and depositional behaviors, to be understood. A classification scheme for anthropogenic materials will broaden the scope of sedimentology and consequently traditional geoscience, enabling deeper analysis of environments from beaches to landfill deposits. Through revealing complexities in the dispersal of anthropogenic materials, we could provide critical predictive insights for locating areas for cleanup efforts, as well as anticipate the environmental future of Earth.

In this paper, a comprehensive classification framework for anthropogenic materials is proposed, which aims to create a more precise system for documenting the mineralogy, structure, and inter-grain relationships of anthropogenic sediment, and mixtures of sediment and anthropogenic material. The new anthropogenic sediment framework is built on the foundation of methods that are well-established in traditional sedimentology, which specifically includes: i) bed-scale and grain-scale descriptions; ii) sedimentary structures and facies; and iii) nomenclature. The classification will allow us to incorporate anthropogenic materials into our deeper understanding of the geological record of Earth, allow for improved management of mismanaged materials in the environment, aid the prediction of material behavior and its environmental impact, and foster a deeper understanding of the impacts of human-induced change.

DEVELOPMENT OF THE CLASSIFICATION SCHEME

To enable continuity between traditional and contemporary techniques, the proposed classification framework is purposefully grounded in established sedimentological principles (e.g., Tucker & Jones, 2023) and integrates traditional models and techniques with the novelty presented by anthropogenic materials. The core strengths of sedimentology lie in its required objective observation over interpretation, which in turn enables a deeply rooted allowance for temporality, i.e., we can understand the past and potential future of a deposit from its static form, thereby underpinning current techniques in applied stratigraphy (Koutsoukos, 2005). The success of the traditional sedimentological framework partly lies in its adaptability, which is essential due to the inherent variability of both natural sediment and human-made materials. Mirroring this adaptability, this new framework for anthropogenic materials is appropriately designed to provide a robust foundation for descriptors and nomenclature, such that the most appropriate facies scheme can be developed to meet the specific objectives of a study. The framework presented here specifically focuses on the description of field-scale sedimentological descriptors, however the scheme can be readily used in any environment, including a laboratory. The central reasons for this approach are that by focusing on objective descriptors, we can use the framework relatively inexpensively, and it is also readily usable as the techniques are familiar and within the technical capacity of traditionally trained geoscientists.

Some anthropogenic materials have been processed and buried by us, and some have been processed under the mechanics of sedimentary systems in the environment. Due to its longevity in the environment and exceptional distribution across Earth, plastic has received most of the attention for studies on anthropogenic materials, yet many other materials are abundant and need investigation as well (Kiessling et al., 2019). The framework refers to everything human-made, managed, or refined, as "anthropogenic material". The framework presented here is intended to tie in with Russell et al. (2025), which outlines how to sedimentologically classify the grain characters for individual clasts and whilst it is for plastic as the focus, the approach can be directly related to any sedimentary particle in the environment. Fundamentally, it is objectively accurate that all materials free to move on the surface of Earth are sediment, which has been recognized in relation to plastic by Kane & Fildani (2021), however, it is too confusing in the language of traditional sedimentology to term it "sediment" when we are comparing mixtures of traditional sediments with novel ones. For example, plastic mixed with sand would become a discussion of sediment and sediment, which is unclear. An option is to consider them "natural sediment" and "anthropogenic sediment", but "natural" is a challenging word because our whole environment is at least secondarily impacted by human-induced climate change (Intergovernmental Panel on Climate Change, 2021). As such we discuss "anthropogenic material" and "sediment / matrix". The approach outlined in the framework below helps us unify language, observation, quantification, and understanding surrounding anthropogenic material mixed in with sediment across the environment.

THE CLASSIFICATION SCHEME

The classification scheme that follows has been developed to be an adaptable and flexible framework such that researchers may better describe the evolving geological record. No part of the classification is designed to be used in isolation as it all contributes to the understanding of the material and deposit in question. The classification framework is scale independent, such that whilst we refer to "bed-scale" characteristics, they may also be applied to laminations (beds ⩽ 1 cm), as equivalent to traditional sedimentology. It is important that the following scheme is applicable to all scales because a plastic sheet will perhaps only be 1 mm thick, but have substantial, geologically relevant impacts on the drainage and properties of its immediate and surrounding area.

In geological science, we are only expected to perceive what we have the analytical capacity to observe, such that it is expected that there will be uncertainties regarding the origin and precise composition of some materials if we are approaching them in the field, compared to a well-equipped laboratory. Thus, a level of pragmatic limitation is normal and accepted in sedimentological science, allowing for work to be carried out without overarching standards that rely on access to facilities. With anthropogenic materials we have the additional challenge that the presence of materials may involve politics, economics, and many other factors, besides the natural physical factors of the environment, along with substantial novelty that may require an element of education. Here, we manage these challenges by focusing on descriptions of geological relevance, i.e., objective descriptions before interpretations, such that if the interpretations need to change when more information is introduced, than that can occur independently of the descriptive data collected (Russell et al., 2025 – section 3). Therefore, through building on known approaches and aiming the practice at field scientists, we can apply an existing skill set to a new challenge, within which, the scale and detail of observation will be circumstance dependent. As such, a field-ready summary sheet of the scheme may be found in Supplementary Material, however, the full guide below ought to be read before implementation.

Composition

Composition refers to what comprises a material and quantifications of its components therein, which in turn enables understanding of the material's inherent properties, such as density, durability, and reactivity. For anthropogenic materials, it can be particularly important to assess the composition to aid predictions of the material behavior, its environmental impact, durability, and for developing strategies to recycle, reuse, or manage the deposit. Standard sedimentological techniques (e.g., Reading et al., 1996; Tucker & Jones, 2023) remain appropriate for considering the sedimentary components of the deposit; however, the anthropogenic material adds structural and other dynamic complexities that needs recognizing. The approach to using this framework for assessing the composition of anthropogenic material and sediment mixtures consists of three parts (Fig 1).

The first part focusses on the characteristics of the anthropogenic material. The fundamentals of how to better describe plastic grains and clasts as a sediment are covered in Russell et al. (2025), which focusses on characteristics that aim to better clarify how these materials act as sediment via assessing clast size, shape, total density, and material properties. Importantly, even though the classification framework features plastic, it can be applied to any natural or anthropogenic material, such as metals, glass, bricks, and composites.

The second part considers the sediment around the anthropogenic materials using classic sedimentological techniques, such as assessing the grain shape, mineralogy, and grain size. Assessing the sediment is crucial for defining a relative context for how anthropogenic materials behave and are distributed in the environment in order to allow for an improved, connected understanding into traditional sedimentological models and concepts. Anthropogenic material and sediment mixtures may not always be found in

Figure 1. A summary of the three-part methodology for assessing mixtures of sediment and anthropogenic material.

natural environmental settings, it may be that 100% of a deposit is anthropogenic material, such as landfill sites. In these contexts, traditionally understood sedimentary sorting processes are unlikely to apply, however, it is critical to identify and describe mixtures to achieve a comprehensive environmental understanding.

In the third part, materials within the anthropogenic material are considered, such as the contents of a bottle. The enclosed material may be sediment or anthropogenic in nature itself and therefore, any combination of grain analysis and other elements of the first two parts of the approach can be utilized. Any materials within anthropogenic material could hold sedimentological deposits that are spatially or temporally misaligned with the surrounding environment. The anthropogenic material may be fully contained (such as a bottle with a lid on), or semi-contained, (such as a bottle with the lid off). It is important to consider this aspect, and consider it separately, because materials that themselves are enclosed in an item of anthropogenic material may alter the density of the clast and possibly be ex situ.

Overall, all three parts of the methodology may not be required; for example if there is no contained or semi-contained material, the third part is not necessary. As such, execution of this methodology will depend on the specifics of the sediment and anthropogenic material.

Lastly, in each case there are varying degrees of human impact, whereby the material may have been: i) passively formed within a sedimentary system; ii) actively created or altered by human activity, or iii) formed through a combination of passive sedimentary and active human processes. Alterations include human-made or naturally derived material that has been anthropogenically managed, relocated from its original location and/or had one or more bed- or grain-scale characteristics altered. It is important to note both objective evidence alongside interpretations regarding if the materials or accumulations have been actively or passively developed (or a combination therein), such that we can better understand the driving forces behind the distribution and re-distribution of global resources.

Bed-scale Characteristics

At the bed (or lamination) scale, the classification focuses on terminologies that speak to the broader-scale material properties of the layer, which will enhance the interdisciplinary utility and inform the engineering assessment of the ground's properties (Fig 2). Additionally, it will aid geologists in determining factors such as the preservation potential of the anthropogenic material in its present state and assess its likelihood of becoming reworked or redistributed. Although this classification framework is scale independent, it does aid in the practical application of the scheme to have a large-scale starting point, although this approach may also be applied to a lamination / grain-scale study.

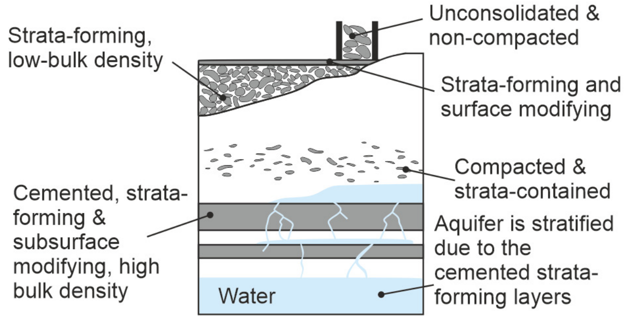

Figure 2. A figure to demonstrate the principles of the bed-scale characteristic descriptors.

The characteristic descriptors are in four pairs (and two individuals), but a description does not necessarily need to be binary (e.g., either strata-forming or strata-contained). For the typical detail expected from a field study, the descriptors are likely to be sufficient, however, for a more detailed survey, additional quantifications such as the degree of compaction or intermeshing may be valuable. As such, the bed-scale character framework is adaptable, with the provision for the incorporation of additional definitions and detail, provided that these foundational criteria are first considered (Table 1).

Grain-scale Characteristics

At the grain-scale, the classification framework focuses on grain, or clast, properties and inter-clast-relationships (Fig 3), such that we can broaden the sedimentological context of contemporary field sites. The distinction between sediment matrix and a clast is typically carried out in a relative context, as in traditional sedimentological studies (e.g., Tucker & Jones, 2023).

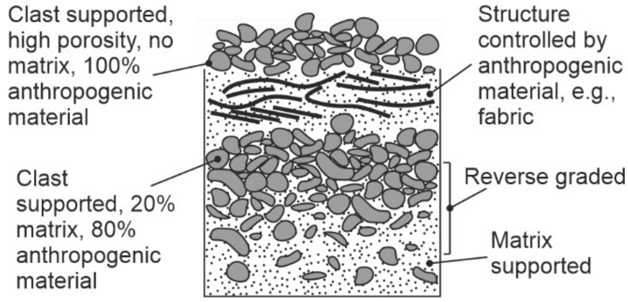

Figure 3. A figure to demonstrate the principles of the grain-scale characteristic descriptors.

Some of the following categories are paired but do not need to be considered as binary in nature. As long as the central criteria are considered, additional categories, subcategories, and details may be added to address the requirements of specific studies (Table 2). Lastly, these categories may overlap, as a single clast may require both bed- and grain-scale characteristic descriptors to capture its environmental positioning.

Table 1. The description and significance of bed-scale characteristics

	Description	Significance
Strata-forming	Dominates the structure and stratigraphic architecture of the deposit. May initiate a new sedimentation process.	Understanding whether anthropogenic materials have acted as agents in the creation of strata or as additions within the strata, informs us about the history and dynamics of anthropogenic impact and aids in reconstructing past environmental conditions and predicting future geological developments.
Strata-contained	Clasts are interspersed and embedded within existing sedimentary layers without markedly altering the stratigraphy.	
Surface-modifying	Deposited material causing alterations to Earth's surface may be called morphostratigraphic or surface-modifying, and it affects erosion, deposition, landform evolution, topography, albedo, roughness, and/or hydrology.	Surface modifying strata are typically more visible and have immediate impact on land use and ecosystems. Subsurface modifying materials impact geotechnical properties, groundwater flow, and even soil fertility, resource extraction, and contamination pathways.
Subsurface-modifying	The materials influence the textural and compositional properties of subsurface strata through affecting the layering, compaction, or chemical composition.	
Cemented	Sedimentary and anthropogenic material is bound to other grains due to precipitated mineral growth, or chemical change, therefore the pore space is reduced from its unconsolidated equivalent. The material may be considered lithified and may or may not be compacted.	The level to which materials are bound impacts the physical properties and behavior of the materials. It affects the mechanical stability and erosion resistance potential of the material, as more unconsolidated material is easier to transport, and is thus susceptible to erosional processes. It is critical to understand, so that we have a full view of the potential geological processes, potential challenges of resource extraction, and the stability of structures and infrastructure that may be built upon or within these materials.
Unconsolidated	Materials are loose, unbound, and uncemented. They may retain their original porosity and permeability, though may be comprised of compacted clasts.	
Compacted	Materials that have reduced porosity and increased density, having been subject to pressure. They have increased mechanical strength.	The differentiation between compacted and non-compacted materials is significant for various aspects of geoscience, including sedimentology, hydrogeology, and engineering geology. Compaction affects the material's hydraulic conductivity, and mechanical properties. Non-compacted materials will be more prone to erosion and reworking.
Non-compacted	Materials that have not experienced significant pressure, such that they are more likely to have maintained their original arrangement, structure, and porosity.	
Intermeshed	Materials that are closely joined or connected via being intertwined or interlocked but not cemented. Such intermeshing may occur via interlocking shapes, entanglement, or close packing, which itself may result from compaction.	Understanding whether materials are intermeshed is crucial for sedimentology and engineering, as it impacts erosion resistance, groundwater flow, and geotechnical stability.
Bulk density	The measurement of a mass of particles within a given volume of sediment or rock, inclusive of pore space.	Bulk density is an important parameter in various fields such as sedimentology, civil engineering, and hydrogeology as it aids in determining the stability and overall mechanical and hydrological properties of the materials, as well as potential spread of contaminants.

Table 2. The description and significance of grain-scale characteristics

	Description	Significance
% Porosity	Porosity is the percentage of a material's volume that is occupied by voids or pores, that may be filled with a gas or liquid. The size, shape, and distribution of the pores are important and contribute to understanding the permeability of the material.	It is important to understand water movement and contaminant dispersion as it is essential for groundwater management and environmental assessments. Porosity and permeability are key to understanding the interactions between water, pollutants, and anthropogenic sedimentary facies, which can inform infrastructure planning and policy.
Permeability	Permeability is the property of a material that gauges its ability to transmit fluids through its interconnected pore spaces. It may be that not all of the material in the deposit is permeable, and this variability ought to be noted.	
% Sediment/ Matrix	A quantification of the proportion of a deposit (by mass and/or volume) that is composed of natural sediment, which may be a main component of the material and/or fine-grained material filling the spaces between the clasts.	The comparative percentages of sediment/ matrix and anthropogenic material allows a discernment of the relative contributions of different depositional processes versus anthropogenic inputs. There may be a degree of uncertainty if the sedimentary materials are very fine grained and microscopic examination is not available. If so, simply describe the materials and state the limitations with approximate percentage estimations. These quantifications are independent of other metrics and specifically refer to the percentage relative volume between natural and anthropogenic materials.
% Anthropogenic material	A quantification of the proportion of a deposit (by mass and/or volume) that is composed of anthropogenic material. This includes any materials that have been generated artificially, as well as materials that have been reworked by humans, which could mean sieving, sorting, redistributing, crushing, etc., otherwise natural sediment or organic matter.	
Clast supported	Texture in which the larger clasts are in contact with each other. The framework of the material is maintained by clasts, and if matrix is present, it surrounds this framework.	In the natural environment, clast- supported textures typically indicate higher velocity transport conditions over matrix-supported ones (e.g., a debris flow as compared to hemipelagic fallout). In anthropogenic environments, such formational relationships may not be as clear. Whether a deposit is clast or matrix supported may impact its permeability, bulk density, and other properties.
Matrix supported	Texture in which the finer-grained matrix material is sufficiently abundant to separate the clasts from each other, such that the matrix supports the clasts in the deposit.	
Sedimentary structure controlled by sedimentary processes	The structure within a sedimentary deposit has been controlled by sedimentary processes, such that the physical and geometrical arrangement of particles has been primarily influenced by natural mechanics such as erosion, transport, and deposition (e.g., cross-bedding).	Determining whether the internal structure of a sedimentary deposit is naturally-formed or if it has either passively or actively affected by anthropogenic material is not an easily quantifiable characteristic, however, it is important to note as it highlights the contrast between what may have been present without human influence compared to an anthropogenically impacted reality. As such, it is relevant to many disciplines as an important step toward comprehending the changes that we are making to the stratigraphic record of Earth.
Sedimentary structure controlled by inclusion of anthropogenic material	Human-made materials have had a significant influence on the inter-clast relationships, i.e., the textural and/or structural aspects of the deposit are impacted, and the pervasive nature of anthropogenic components suggests that sedimentary structures were not able to develop naturally.	
Sorting	The consistency, or homogeneity, of grain sizes within a sedimentary deposit, range from very well-sorted, wherein the grains, or objects, are the same scale, characteristics, and composition (i.e., homogenous), to very poorly sorted, wherein the grains, or objects, markedly differ (i.e., strongly heterogeneous).	The degree of sorting within a material provides valuable information about sources, past transport processes and the nature of the deposit. If human activities relate to the transport and any mechanical sorting of the material, then this also counts as a sorting process, as the results of it may persist into the geological record.
Orientation	The spatial arrangement of sediments or clasts within a deposit.	The orientation of clasts can reveal information about natural environmental deposition (e.g., flow direction) and anthropogenic influences (e.g., mechanical compaction), which are important to understand the processes that shaped a deposit.

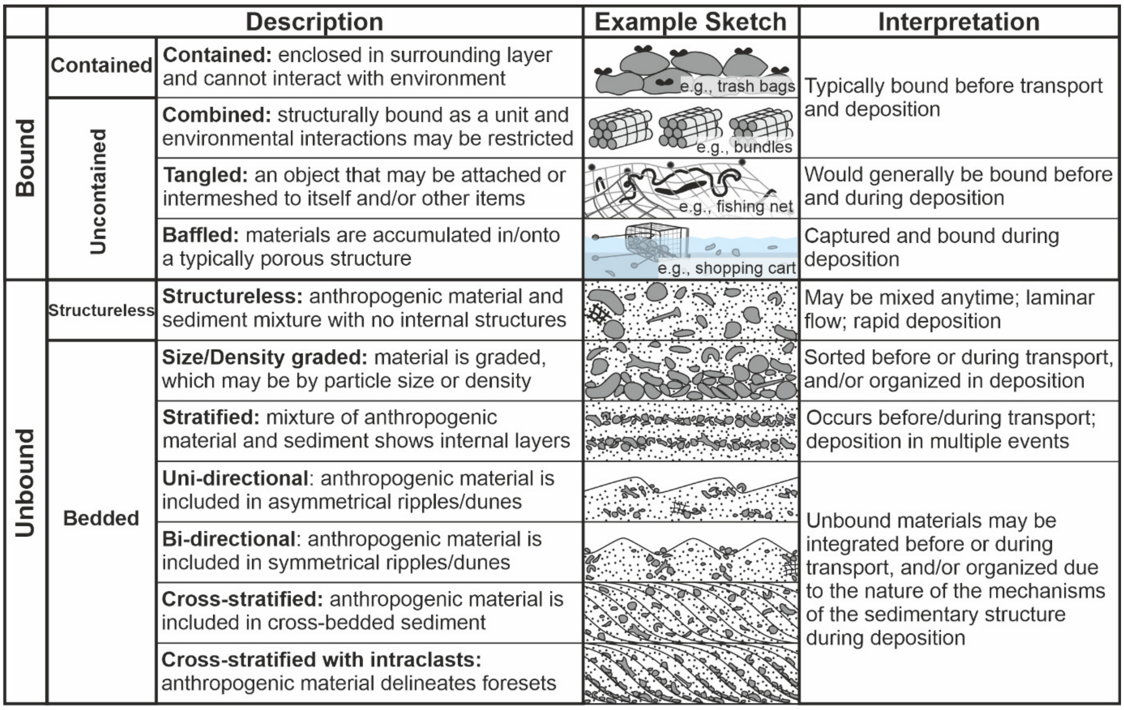

Figure 4. A summary table of the framework for describing sedimentary structures including or entirely of anthropogenic materials that may or may not contain sediment.

The dotted texture for unbound materials may be sand, carbonates, soils, anthropogenic materials, another material, or any combination therein. Where anthropogenic material has been included in the images, it is not intended to impose a scale dependance for the sedimentary structure, it is simply intended to serve as an example.

Sedimentary Structures

Sedimentary structures are one of the primary frameworks of description and observation by which sedimentologists understand the past dynamics and processes of sedimentary systems. However, sedimentary structures now potentially integrate anthropogenic materials and processes within the natural processes of sediment erosion and deposition to varying degrees. Additionally, the presence of anthropogenic materials is leading to more complex dynamics, which challenges us to revisit and expand our sedimentological approach. To avoid unnecessary reinvention of concepts and terminology, sedimentary descriptors were studied from across the discipline such that existing principles can be adapted. Whilst much of the resulting categorization is widely used and familiar within siliciclastic systems (Collinson & Mountney, 2019; Tucker & Jones, 2023), the concept of 'bound' and 'unbound' is taken from the Dunham classification for carbonate sedimentary rocks (Dunham, 1962), and bafflestone presented further inspiration. The remainder of the inspiration came from experiencing and investigating the range of combinations of sedimentary structures in the environment, spanning both natural and anthropogenically controlled depositional environments, as outlined in Figure 4.

Within this broadened context, sedimentary structures accommodating anthropogenic deposits are classified into two main categories: bound and unbound. Bound structures indicate a degree of adherence between the materials and are sub-categorized as either 'contained', i.e., in bags or boxes, or 'uncontained'. Contained structures refer to individual materials that are enclosed into a unit which may restrict their environmental interaction. Bound, uncontained structures are further differentiated into: 'combined', where anthropogenic materials are structurally bound as a unit and may be cemented (e.g., pyroplastics) or unconsolidated and mechanically tied together (e.g., gabions); 'tangled', where the material is unstructured and has become attached to itself and/or other items, including organic materials and marine organisms; and 'baffled', where materials have become accumulated into or onto a dominant, typically porous, structure.

Conversely, unbound structures lack this material-controlled internal coherence and hold more similarity to typical sedimentary structures. Unbound materials may be structureless or bedded. A structureless (or 'massive') deposit signifies no internal structure. Bedded materials are sub-categorized as: 'size or density graded', which suggests a change in condition or input through deposition, for example selective sorting by fluid movements during transport; 'stratified' indicates layering, which may occur at any scale; 'uni-directional' or 'bi-directional ripples' ripples/dunes signify the influence of directional currents on deposition. Additionally, features such as 'cross-stratified or 'cross-stratified with intraclasts', should be recognized. These two features are focused on here for brevity and simplicity as they are common, however, anthropogenic materials may be incorporated into any sedimentary structure, e.g., load and flame structures, convolute bedding, or tidal bundles. The full range, and typical inter-relationships of stratigraphic morphology ought to be considered and recorded when exercising this analysis framework in field studies, e.g., in baffled sediment, you may see stratified sediments with uni-directional cross-stratification.

The interpretation for each category is inherently linked to the history of the material's journey before and during transport, and throughout its deposition. 'Contained' and 'combined' materials are typically bound before transport, whereas 'tangled' materials generally became intertwined during transport but before deposition, and 'baffled,' materials are predominantly captured and bound by a main structure during the depositional processes. For unbound deposits, structureless material may have been mixed before, during, or after transport, though may also be a deposit from a laminar flow, or perhaps a rapid depositional event. The sorted and stratified bedded materials indicate deposition, perhaps over multiple events, with materials being organized during transport and/or deposition. Bedforms such as ripples and dunes may incorporate materials during transport as their sedimentation processes are laterally dynamic, such that materials are organized into the sedimentary structure during deposition. Of course, there are many known and unknown nuances to the processes and depositional mechanisms of sedimentary structures, which may be found in literature of traditional sedimentology (Collinson & Mountney, 2019), in turn, perhaps made more complex by the presence of anthropogenic materials (Russell et al., 2023). Each traditionally understood structure requires further study and appropriate integration as we continue to learn and understand anthropogenic materials as part of these sedimentary systems. Through refining these observations and understanding via the outlined categorizations, we are better able to reconstruct contemporary environmental histories.

Nomenclature

A proper nomenclature framework ensures consistency, connectivity, and clarity, which encourages interconnected research and easier collaboration. In traditional sedimentology, facies classification schemes have been developed, which are based on the mineral composition of the sediment, such as the Dunham classifications for carbonates (Dunham, 1962), and biochemical and evaporitic sediments (e.g., Hallsworth & Knox, 1999). As such, the proposed scheme focusses on highlighting the dominant mineralogy of the material. This approach is a continuation of the emerging nomenclature preferences of the community, e.g., plastiglomerate (Corcoran & Jazvac, 2020), plasticlast, and plastisandstone (Rangel-Buitrago et al., 2023).

There are 60 possible combinations presented in Figure 5, which are objective and broad, such that they may be readily applied and interrelated between studies. The approach is readily extendable, just ensure that any added term is not interpretive, which eliminates terms such as 'car-glomerate', as a car is an interpretive term for a metalliclast. Of course, the descriptive notes can discuss the name 'car', but the primary identifying nomenclature critically needs to be interrelatable to endure in a sedimentologically useful capacity, which is explained in detail from base principles in Russell et al. (2025).

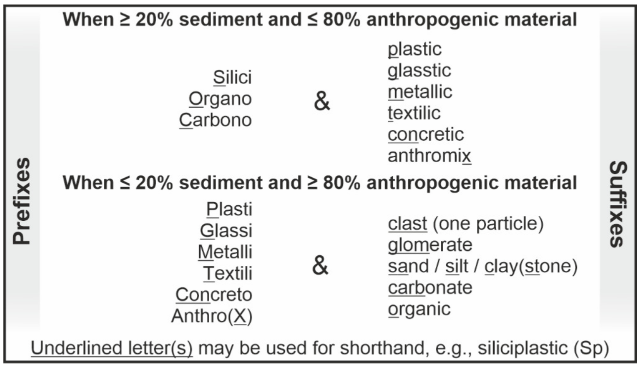

Figure 5. Nomenclature for naming anthropogenic materials that may be mixed with sediment.

The nomenclature approach here is a combination of the appropriate prefix and suffix, which is determined by the proportion of sediment to the anthropogenic material by volume, the dominant type of anthropogenic material, and the grainsize. If possible, it is also helpful to determine the mass of the material proportions as well as the volume, as this is a helpful metric for bulk density calculations, global flux assessments, and the development of plastic pollution budgets. The threshold between the two core categories for nomenclature aims to delineate the dominant structural component of the deposit. To determine where the threshold would be, a benchmark was derived from the mathematically determined porosity (φ) of a material made of spheres that are hexagonally close packed (packing density (PD) 0.74), so using the equation $\varphi = 1 - PD$, we find that the porosity (φ) in this close packing is 26%. However, a facies of equally spherical clasts is rare, therefore, to allow for some irregularities, the threshold or proportions of sediment and anthropogenic material between the core categories has been set at 20% and 80%.

When there is greater than or equal to 20% sediment and less than or equal to 80% anthropogenic material, the possible prefixes are 'silici-', 'organi-', and 'carbono-', (referring to silica, organic materials, and carbonates). The suffixes are '-plastic', '-glasstic', '-metallic', '-textilic', and '-concretic' which refer to the dominant mineralogy of the anthropogenic material as plastic, glass, metal, textiles, or concrete. If there isn't a dominant mineralogy, then the suffix '-anthromix' should be used, designating it as a sediment containing a mixture of anthropogenically-derived material. When there is less than or equal to 20% sediment and greater than or equal to 80% anthropogenic material, the possible prefixes are 'Plasti-', 'Glassi-', 'Metalli-', 'Textili-', and 'Concreto-' which refer to the dominant mineralogy of the anthropogenic material. If there is no dominant mineralogy, or the dominant material isn't listed, then the prefix 'Anthro-' may be used. The suffixes refer to the scale, and quantity, of the particles being described via '-clast', '-glomerate', '-sand(stone)', '-silt(stone)', '-clay(stone), '-carbonate', and '-organic'.

Some examples of the 60 possible nomenclature combinations are siliciplastic, metallisandstone, and anthroglomerate. It is worth noting that anthroglomerate is a very broad term, so can refer to both unconsolidated and cemented mixed anthropogenic material, therefore covering a bag of trash through to structures, such as buildings, composed of different materials. Additionally, it is used to refer to all materials that are combined or contained, even for naturally occurring sediment, because it has been anthropogenically packaged into that state prior to transport, so it is anthropogenically altered (e.g., a plastic bag of builder's sand would be a contained clast of anthrosand).

As outlined in Figure 5, there are codes associated with this nomenclature that enable easy recording of the materials into the standard techniques for taking records in the field such as "Sp" for siliciplastic material. Additionally, if there is a mixture of materials of two dominant mineralogies, such as plastic and glass in a recycling plant, the name may be stacked such that it would be a Plastiglassiglomerate, with the arrangement reflecting that plastic is more prevalent than glass in this deposit. Any more than two dominant mineralogies should not be stacked as the words become unwieldy.

As this is simply outlining a nomenclature framework, the options listed in Figure 5 are not intended to be exhaustive. It intentionally serves as a foundational framework that can be built upon objectively to fulfil the remit of a study, so long as the additions are indeed objective (see Russell et al., 2025). Some examples of potential additions are ceramic, asphalt, mud(stone), and granule(stone), which could allow for "asphaltglomerate", or "ceramigranulestone" if needed for a study.

APPLICATIONS

By using these classifications, it increases the capacity of sedimentology to discuss anthropogenic materials, interlink with other disciplines, and to compare between field sites. It will aid in collecting and presenting data for: environmental impact assessments, geotechnical analysis, resource management, archaeology, regulatory framework and policy development, and cultural and historical documentation.

Primarily, the direct application of this classification scheme is that it offers a standardized approach for insights into how to sedimentologically describe and interpret anthropogenic materials, which in turn presents opportunities for more advanced interpretations. By describing novel materials and mixtures using these methods, we can adapt traditional geological methods, such as mapping, so that we can understand the spatial distributions of these materials and their potential impacts on the environment. We may also incorporate the descriptions into sedimentary logs when we come across anthropogenic materials. Such applications would not require any substantial deviations from traditional approaches, it would simply be an integra-

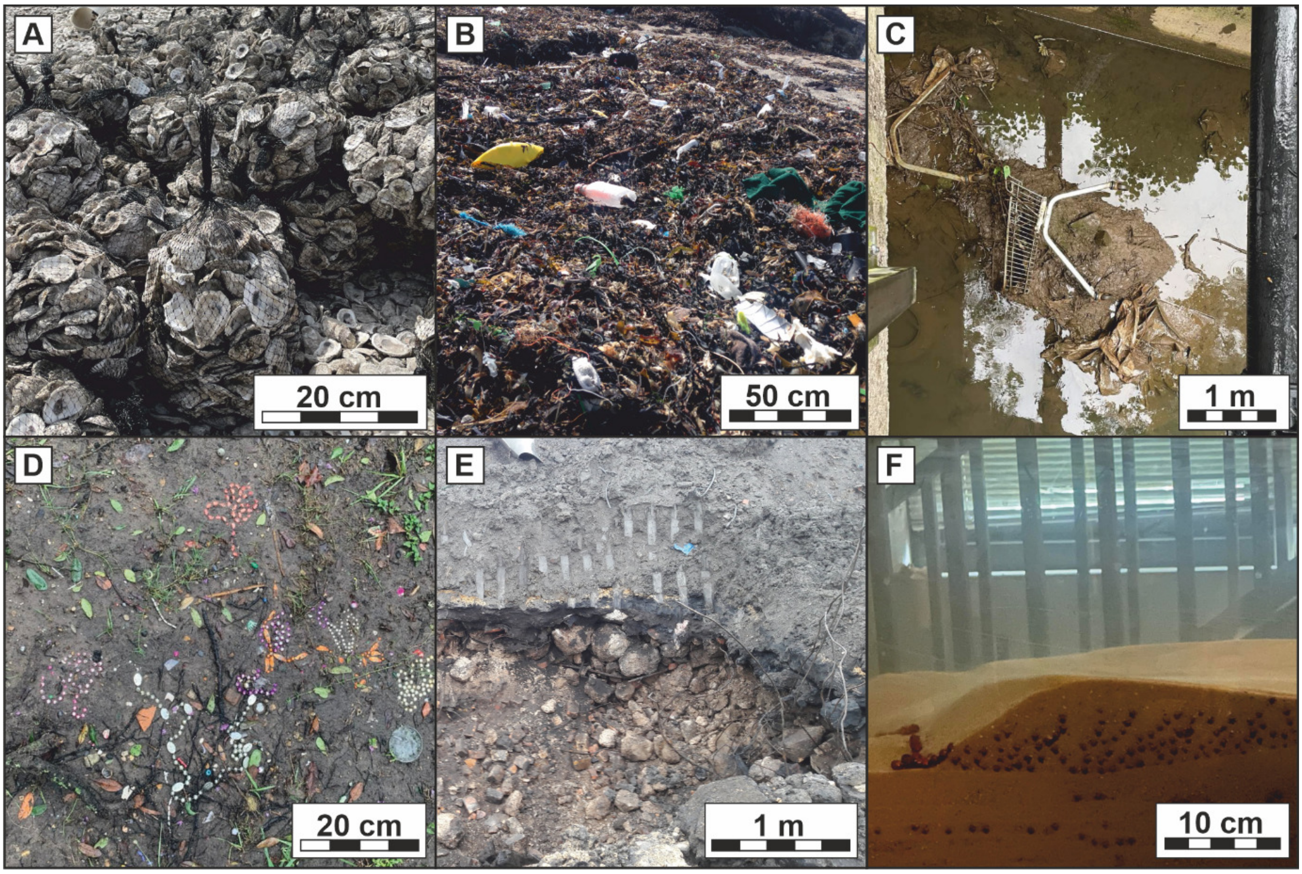

Figure 6. Photographs demonstrating anthropogenic sedimentological deposits in a range of environments.

The names of each deposit are: A – Combined Anthroglomerate, B – Structureless Organoplastic, C – Baffled Silicimetallic, D – Structureless Organoplastic, E – Stratified Anthroglomerate, and F – Uni-directional Siliciplastic.

tion of further terminology and variability to deepen our understanding of the recorded trends. Figure 6 is a compilation of images of representative examples of anthropogenic materials in the field and laboratory. Each example demonstrates varying degrees of human impact, whereby the activity and process of formation may have been passive as part of a sedimentary system, actively altered or created by human activity, or a combination therein.

A – Combined Anthroglomerate. Organic clasts are combined in plastic nets with a mesh size of 1 cm. The mesh size of the nets means that the environmental interaction of the organic clasts is restricted but not prohibited, so they are combined not contained. The units are strata-forming, surface-modifying and unconsolidated, and the organic clasts are also unconsolidated. The material is uncompacted with a low bulk density. They have a high porosity and permeability and are 100% anthropogenic material. Whilst the oyster shells in the nets are of course organically grown, they were manually sorted from restaurant waste, transported to this site, and gathered into plastic nets, to then be redistributed along the coastline. As such this is definitively a natural material that has been actively altered by human activity, so we note that the bound material will carry the prefix "anthro-". It is clast supported, the structure is controlled by the anthropogenic material, and the shells have no preferred orientation. The deposit is bound, uncontained and combined. There is more than 80% anthropogenic material so the name of this deposit is anthroglomerate.

B – Structureless Organoplastic. The wrack contains anthropogenic materials, of which the dominant mineralogy is plastic. The mixture is strata-forming, surface modifying, unconsolidated, non-compacted, and intermeshed, with moderate bulk density. The material has high porosity and permeability; the organic material is around 90% of the deposit and the anthropogenic material is around 10%. It is clast supported, and the structure is controlled by the sedimented organic material. It is very poorly sorted and some of the net and rope has become oriented perpendicular to the direction of wave approach. The deposit is unbound and structureless with tangled components throughout, and it is organoplastic.

C – Baffled Silicimetallic. The two shopping carts are surrounded by sediment, organic material, and anthropogenic materials. The deposit is strata-contained, surface-modifying, unconsolidated, and uncompacted, with a moderate bulk density. Whilst the dominant metalliclasts are very porous and permeable, the matrix has low porosity and permeability, and the deposit in total composed of around 60% sediment and 40% anthropogenic materials. The structure is controlled by the anthropogenic material and there may be sorting and orientation, which is not observable from this vantage point. The deposit is bound, uncontained, and baffled, such that it is a silicimetallic deposit.

D – Structureless Organoplastic. The Mardi Gras beads are embedded into the soil, forming a strata-contained deposit that is subsurface modifying. The deposit is cemented and compacted, with a moderate to high bulk density. The deposit has moderate porosity and permeability and is composed of 15% anthropogenic material and 85% organic soil. From the observed angle, the deposit is unbound and has no structure, sorting, or orientation, so is structureless with some tangled components, though in cross-section it may be stratified. The deposit is organoplastic.

E – Stratified Anthroglomerate. The building waste debris is strata-forming, with some strata-contained components such as the metal rebar on the right of the image. It is subsurface modifying, unconsolidated, and the matrix is compacted. The material has a high bulk density, moderate porosity and permeability, and is composed of 100% anthropogenic, or anthropogenically modified, material as it has been actively accumulated by human activity. The lower part of the deposit is clast supported and the upper half is matrix supported, delineated by a sharp contact. The structure is controlled by the anthropogenically determined distribution of the material, but the deposit is very poorly sorted with no preferred orientation of clasts. The structure is unbound, bedded, and stratified, whilst the layers themselves are unbound and structureless, and the deposit is named an anthroglomerate.

F – Uni-directional Siliciplastic. The image is from an experimental flume tank, which enables us to consider a cross section of the sandy deposit containing Mardi Gras beads. The deposit is strata-forming, (experimental riverbed) unconsolidated, and uncompacted, with moderate bulk density. The deposit has moderate porosity and permeability. The proportions of plastic and sand are known to be over 99% sediment and less than 1% beads, though in this cross section the deposit appears to contain around 10% anthropogenic material. The deposit is dominantly matrix supported, though clast supported in some places, and the structure is controlled by the sedimentary processes. There is no preferred clast orientation as the particles are spherical, though there is some sorting in how the beads have been organized into the sand deposit (e.g., Russell et al., 2023). It is an unbound, bedded, uni-directional deposit with the feature of cross bedding with intraclasts, and named siliciplastic.

The classification scheme is not designed to be exhaustive, but to provide a framework that may be built upon based on the objectives of a project. The descriptions make it possible to determine an objective analysis of anthropogenic sedimentary facies that speaks to its depositional characteristics, which in turn will enable the broader-scale environment to be assessed. If the deposit has needed to be removed, sectioned, or dismantled to any degree in order to access the required information and context, then this should be noted in the field description.

CONCLUSIONS

The framework presented offers a unified starting point from which we can evolve and develop our understanding and descriptions of anthropogenic material, enabling us to better track our impact on Earth. The improved classification of anthropogenic materials and their relationship with natural sediment will aid interdisciplinary collaboration via enhanced research communication of the new objective principles of our environment. By integrating these novel materials into traditional sedimentology, a more nuanced understanding of the impact of anthropogenic materials on sedimentary processes and the surrounding environment can be developed.

The scheme is largely based within recognized geological classification systems, and thus it is readily usable by traditionally trained geoscientists. The classification scheme is thorough and adaptable, such that it can integrate future changes and discoveries without losing descriptive accuracy or interpretive power. Through using this scheme and learning more about our environment, we will learn more about the significance of anthropogenic influence in the present and future the stratigraphic record.

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Supplementary Materials

Supplementary Material

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