WORLD AS SEDIMENTS

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ABSTRACT: Sediment as a concept and metaphor has been employed to characterise a large variety of processes and structures, ranging in nature from material, to social and conceptual. The prototypical notion of sediment used in such characterisations often mirrors that of geological sediments. Despite their variety and ubiquitousness here on Earth, geological sediments are unduly restrictive and special in nature. In particular, they are solid, fossilised, layered and no longer in a continued state of formation.

Here I consider the concept of sediments from a wider, cosmological, perspective by treating them as spatiotemporal outcomes of interrelated nonlinear dynamical processes, on vast scales of space and time. Such sediments are generally non-solid, non-fossilised, ongoing and able to impact the processes that are giving rise to them. They can take multitudes of forms, including sediments that are not accumulative/additive and layered as in the case of geological sediments, but subtractive and/or non-layered/dispersive or a combinations of these — as well as others that are in principle closed to observers, such as black holes. There are also sediments which are non-material, such as those in electromagnetic fields (light), including those that are manifestly spatiotemporal.

Seen from this perspective the observable Universe could be looked upon as an enormously complex and interrelated web of diverse and novel sedimentary processes and structures coming into being and withering away — often involving chaos and contingency and at times undergoing cataclysmic metamorphosis, which could in the process drastically impact the environments that gave rise to them, altering their future histories. They generally possess multiple origins and can occur on vast range of scales of space and time, extending from the beginnings of the Universe soon after the Big Bang to its very far future, which is presently unknown, including ourselves as biological beings and observers.

The concept of sediment has also been used as a metaphor to conceptualize various social and conceptual constructs, such as geometrical concepts — which as we shall see can also be extended to the case of Mathematics as a whole.

A key distinguishing feature of sediments is how they relate to time, not only in terms of their lifetimes, which can take a vast range, including sediments with lifetimes enormously longer than the present age of the Universe, as well as mathematical sediments that appear future eternal —

but importantly also by the way they encode time: explicitly (as in layered sediments), implicitly (as in non-layered dispersive sediments), and implicitly with ruptures (as in cataclysmic sediments).

The generalised notion of sediment introduced here provides a far richer framework to conceptualise the sedimentary concept and metaphor in enormously diverse settings, while emphasising the interconnectedness of sediments, their multiple origins, as well as their ongoing, potentially cataclysmic and contingent natures. It also raises fundamental questions regarding their ultimate fates in a transient Universe.

KEYWORDS: Sediments; Transient Universe; Non-geological

PREAMBLE

According to the dictionary definition, sediment is material deposited by water, wind, or glaciers. Judging by this definition, sediments are often thought of terrestrially with geological sediments as their prototypical model. The problem with this definition is that despite their ubiquitousness here on Earth, geological sediments are nevertheless very restricted and special in nature in a number of crucial ways to even account for the vast varieties of sediments found here on Earth. To see their limitations it is instructive to single out some of the key features that specify geological sediments, namely the fact that in addition to being outcomes of dynamical processes like all other sediments, they are: (i) solid, (ii) fossilised, in the sense that they are no longer ongoing, (iii) often possess spatially ordered sedimentary layers which can potentially provide effective time ordering and partial information about the dynamical sedimentary processes that gave rise to them, (iv) spatially connected and localised, which given their terrestrial scales has the consequence of making them appear as effectively spatial (as we shall see below), and (v) possess very long lifetimes[1], relative to our lifetimes as observers, which at times give them an impression of permanence.

Key discoveries over the last century have radically changed the idea of seemingly unchanging nature of geological sediments, and more importantly that of the Universe as a whole. Regarding the former, there were a range of observations which pointed to the immense ages of the geological sediments, on

[1] The oldest rocks discovered on Earth so far are in north east Canada, estimated to be about 4.16 billion years old. See Sole, C. et al., `Evidence for Hadean mafic intrusions in the Nuvvuagittuq Greenstone Belt, Canada', Science, 388, 2025, 1431–1435.

the one hand, and their dynamism on the other. These eventually led to the important discovery of continental drift which highlighted the malleability (fluidity) of the earth's crust on longer time scales despite its appearance of solidity[2]. This planetary scale dynamism in the Earth's crust is due to the convective motion of the Earth's Mantle on time scales of up to 200 million years. Even though this is extremely long relative to our lifetimes, it is still a fraction of the age of the Earth, which means that there has been ample time for a number of such convective cycles to take place during Earth's lifetime, thus implying that most geological sediments we see today are not primary and have been through multiple sedimentary changes and rebirth and thus have multiple origins.

Furthermore, looking at our surroundings on Earth we see a vast range of structures including physical, chemical, biological (including ourselves as living beings), as well as social structures and conceptual constructs, which are all outcomes of dynamical processes and which could be viewed as sedimentary, in the sense defined below, but which do not necessarily share many of the features that specify geological elements.

The restrictiveness of viewing sediments exclusively from a geological/terrestrial perspective becomes far more transparent when we consider a larger cosmological perspective, specially in the light of modern discoveries about the Universe. Perhaps the most important of these, as far as our discussion here is concerned, are threefold: firstly, that the Universe possesses immense scales of space and time; secondly that the fastest speed of propagation of information (the speed of light) though enormous is nevertheless finite — a discovery with two important yet seemingly contradictory outcomes, one apparent and the other real. This fast speed implies that the distance travelled by light in a second is much larger compared to terrestrial scales, which allows geological sediments to be effectively viewed at an instant of time, thus making them appear as effectively *spatial* — while the fact that the speed of light is the same for all observers has the important consequence that the real world is in fact four-dimensional, *spatiotemporal*. And thirdly the fundamental discovery that the Universe as a whole is dynamic, thus profoundly changing the view held for

[2] See for example the articles in Hawkesworth, C.J.; Brown M. (eds), `Earth dynamics and the development of plate tectonics', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376, 2018, 2132.

millennia of a static and unchanging Universe.

Looking beyond terrestrial settings at the vast plethora of processes and structures that populate the Universe, including planets, stars, galaxies, clusters of galaxies, black holes, etc., to variety of fields including electromagnetic fields, we notice that they are all clearly ongoing outcomes of dynamical processes. Nevertheless, they possess very different natures, forms, space and time scales, and importantly they do not all share the features mentioned above that define geological sediments.

Given this enormous diversity, a key question becomes whether there is a sense in which we could treat all such dynamic structures in the Universe as sediments? This would clearly require a more general notion of what constitutes a sediment. We shall see that a general enough definition would be to define sediments as the spatiotemporal outcomes of interrelated nonlinear dynamical processes, whatever form they may take: physical, chemical, biological, electromagnetic, historical, or conceptual, and whatever scales of time and space they may possess. Such sediments are in general dynamically ongoing, non-fossilised, non-localised and unlike geological sediments do not necessarily possess clearly demarcated spatial stratifications, but could be dispersive. Furthermore, they could be accumulative/additive (as is often the case with geological sediments) or subtractive in nature (in the sense that the dynamical processes involved may instead remove parts or layers of structures), or combinations of both. And importantly given the nonlinear nature of sedimentary processes they often possess elements of chaos and contingency.

Below we briefly discuss some examples of different types of sediments that occur in the observable Universe, which are in some ways unlike geological sediments, and discuss some of the interesting issues they raise.

WORLD AS SEDIMENTS

Looking from the above general perspective, the history and evolution of the observable Universe can be viewed as interrelated nonlinear dynamical processes giving rise to the formation, transformation and withering of a vast multiplicity of dynamical outcomes and evolving structures that can be viewed as diverse forms of sediments.

The very earliest phases of the Universe immediately after the Big Bang are not well understood. It is however believed that during this very early epoch the Universe went through a phase of accelerated expansion, the so called inflation, which is thought to have resulted in stretching the initial quantum fluctuations into macroscopic scales, which ultimately acted as seeds for the formation of structures such as galaxies and their clusters that we observe in the Universe today. Soon after the Big Bang, various elementary particles such as photons (the quanta of electromagnetic field and radiation, light) as well electrons, protons and neutrons appeared which as the Universe continued to expand and cool fused to form the nuclei of the earliest atoms (i.e., Hydrogen (H), Helium (He) and traces of other elements such as Lithium (Li)). The Universe was still too hot for neutral atoms to form and as a result the photons (hence light) could not propagate freely. It was only after about ~ 380000 years that the Universe was cool enough for the neutral atoms to form and for light to propagate freely. This first light which is referred to as the cosmic microwave background radiation (CMB) continues to fill the Universe but its wavelengths have been stretched due to the expansion of the Universe into the microwave region of the electromagnetic spectrum (hence the name), which is not visible to human eyes. This first light has etched upon it small temperature fluctuations which reflect the fluctuations in the matter density in the early Universe which can be looked upon as the sedimentary footprints that later seeded the large scale structures observed in the Universe today.

As the Universe expanded and cooled cosmic gas clouds consisting of these earliest atoms were formed which eventually collapsed locally to form the first generations of stars. It is thought that these massive short-lived stars burnt H and He atoms through nuclear fusion to produce more massive atoms before exploding and seeding the cosmic environments with these heavier atoms, with their remnants potentially collapsing to form black holes. In time galaxies (and their clusters) were formed with the quantum fluctuations acting as their seeds[3], and can thus be looked upon as the blown up sedimentary footprints of these fluctuations. And in time new generations of stars with different masses were born, including those with intermediate masses like our Sun (with its rocky planets).

According to our more general definition of sediment given above, we could

[3] The so called dark matter is thought to have played a significant role in these processes.

look upon all these processes and structures formed during the evolution of the Universe as sedimentary in that they are all outcomes of dynamical processes. Nevertheless, they have widely different natures and features which distinguish them from the geological sediments, and thus the sense in which they can be called sedimentary is different in different cases, as we shall see below.

SOME NOVEL EXAMPLES

The vast range of dynamical processes in the observable Universe can be divided into different types depending upon their nature, including those involving material forms; fields; living matter, and historical and conceptual constructs. In the following we shall briefly look at some novel examples of such sediments, which do not readily fit the geological picture.

Material sediments: Stars

As important constituent parts of the observable Universe stars are sedimentary and yet unlike geological sediments, providing a number of novel features. They are mostly gaseous (in the form of charged plasmas) and fuelled by burning lighter elements to heavier ones through nuclear fusion. Nevertheless, depending upon their masses, they vary enormously in their properties, sedimentary natures, lifetimes and fates — as well as their impacts on the cosmological environments that gave rise to them.

Larger mass stars (with masses greater than about ~ 8 times mass of the Sun), have played a crucial role in the evolution of the galaxies, interstellar media and life itself. They have far shorter lifetimes than our Sun (of the order of millions rather than billions of years) — and possess convective (mixing) cores where they burn lighter atoms to progressively heavier ones, eventually ending up with an layered onion-like internal structure with heavier elements at their cores and lighter elements near their surface layers. Thus they can clearly be treated as sedimentary structures with spatial layerings. As the nuclear fusion proceeds, lighter elements progressively burn into heavier elements until the core consists of iron. At that point the fusion process stops as it can no longer yield energy through the fusion of iron. The star's core then collapses cataclysmically under the force of its own gravity resulting in a supernova explosion — constituting some of the most spectacular events in the Universe, with a luminosities comparable to the combined output from billions of stars. In the process the exploding star not only disperses the heavier elements produced during its sedimentary history, including Carbon and Oxygen which are important in shaping the future generations of stars, like our Sun, as well as being vital for the evolution of life, but also produces extremely intense radiation and shock waves that can trigger or inhibit the formation of next generations of stars in their neighbourhoods. What remains of the star after the explosion will collapse into a very different sedimentary structure — a black hole or a neutron star, depending on the initial mass of the star.

On the other hand stars with masses similar to that of the Sun live billions of years and possess outer mixing (convective) layers, with non-mixing cores. The burning of Hydrogen in their centres produces Helium which in time results in stratified layers of plasmas of Hydrogen and Helium. In that sense they can be treated as sedimentary.

In contrast, low mass stars (with masses less than about ~ 0.35 of the mass of the Sun), are wholly convective without spatially layered interiors, since the Helium produced through Hydrogen burning in their central regions are continuously mixed and dispersed. Despite the absence of layerings in their interiors they can still be viewed as sedimentary since they continuously evolve by converting lighter elements to heavier elements and hence possess a memory of their evolutionary history through the proportions of the heavier elements present in them at any given epoch. They thus provide another novel form of sedimentary process which is *dispersive* rather than layered as in geological sediments. Another important feature of such stars (which constitute most of the stars in our galaxy) is that they possess enormously long lifetimes (the smaller the mass the longer the lifetime) up to trillions of years long, which is far longer than the current age of the Universe.

Thus treated as sedimentary processes stars provide novel forms of sediments depending upon their masses: layered sediments in the case of large and solar mass stars, and non-layered and dispersive sediments in the case of low mass stars — with extremely different lifetimes ranging from millions to many trillions of years. Importantly also they provide examples of sediments (as in the case of massive stars) whose cataclysmic metamorphosis dramatically changes and enriches the environment that gave rise to them, before settling down into sedimentary structures of very different kind.

Another important related class of material structures in the Universe, as we saw above, is black holes. They are however very special in that they in principle do not allow access to information about their interiors, with only their overall parameters, namely their masses, electric charges and angular momenta, being accessible to outside observers.[4] Despite forbidding information about their interiors, they can nevertheless be treated as sedimentary in that they are outcomes of dynamical processes which continue to evolve resulting in changes in their overall parameters. This happens through the accretion of matter and energy, resulting in increases in their parameters, and through their evaporation[5] which leads to the reduction in their parameters; outcomes that are in principle measurable in both cases. Their evaporation also implies that they have a finite lifetime, which increases rapidly with the increase in their masses, with the black holes of solar mass or much larger (supermassive black holes) having lifetimes that far exceed the current age of the Universe.

Sediments in EM waves/Light

One of the novel outcomes of viewing sediments from our wider cosmological perspective is to highlight other forms of sedimentations which are distinct from those that occur in material domains. Interesting examples are provided by novel sediments carried by fields, such as electromagnetic waves including sediments in visible light. We have already discussed the sedimentary nature of the cosmic microwave radiation that permeates the Universe. Below I briefly discuss some other novel examples of such sediments.

Optical Images and photographs as sedimentary

It has been demonstrated that optical images and photographs encode time in a novel way which makes them in principle spatiotemporal[6] — and as we shall see

[4] This is due to the so called No-Hair Theorem, according to which all stationary blackholes can be completely characterised by three externally observable parameters: their mass, electric charge and angular momentum. See e.g. Misner, C.W.; Thorne, K. S.; Wheeler, J. A., *Gravitation*, 1973, San Francisco: W. H. Freeman.

[5] Stephen Hawking showed that black holes have a non-zero associated temperature which implies they can radiate and as a result evaporate. Hawking, S. W., `Black hole explosions?', *Nature*, 248, 1974, 30–31.

[6] Tavakol, R., `Time(s) of the photographed', *Philosophy of Photography*, 10:2, 2019, 195-206.

sedimentary. To see this consider the optical image of any object. In general, different points of the object are located at different distances from our eyes as the observer, or the photosensitive plate in a camera as the recorder of the image. Now to form an image, the light from different points of the object must have left the object at different times (depending on their distances from us) in order to arrive at our retina or the camera simultaneously. In the case of the terrestrial objects whose scales are small compared to the distance traveled by light in a second, the differences in times taken for light from the different parts of the object to arrive at our eyes or the camera are small, which given the sensitivities of our eyes or the cameras seem to us as appearing almost simultaneously. This results in the image to appear effectively at a single instant of time, and hence as spatial. For extraterrestrial objects, with much greater spatial scales, the situation is very different. For example, in the case of the optical image of an average galaxy, possessing dimensions of tens of thousands of light years across, the differences in times taken for the light rays from its different points to arrive at us, or the camera, simultaneously would be significantly longer — up to tens of thousands of years apart. Such optical images would therefore be manifestly spatiotemporal, in that the times at each of its spatial points are different, being earlier the further away its location. For still larger galaxies the time differences could be up to few hundred thousand years, which is comparable to the lifetime of our species, a haunting realisation. Such manifestly spatiotemporal images can be viewed as sedimentary, according to our definition above. This is similarly true of the optical images of sections of the Sky, which could be far larger in spatial extent with dramatically enhanced time differences. In this case however the different sources in the sky are not spatially connected (or even gravitationally bound) and therefore the differences in their spatial distances to us and the resulting time differences could be unrelated and seemingly randomly distributed, providing examples of disordered spatiotemporal sediments.

Lyman-alpha forest

Another interesting example of manifestly spatiotemporal sediment is provided by spectrum of the light of the distant quasars and bright galaxies as they travel to us. As the light from such distant sources travels to us they encounter multiple gas clouds possessing neutral hydrogen atoms, each at a different distance from us, hence moving away from us at different velocities and therefore possessing different redshifts. The encounter of the light with the hydrogen atoms in each cloud results in an absorption line in the spectrum of the passing light due to the so called Lyman-alpha electron transition. As the light passes through different gas clouds on its path to us it acquires a sequence of separate absorption lines in its spectrum each at a wavelength corresponding to the redshift of the respective cloud. These sequence of lines in the spectrum of such distant sources is referred to as Lyman-Alpha Forest.[7] They can clearly be viewed as spatiotemporal footprints of the encounter of the light from such sources with different gas clouds along their paths, and hence as sedimentary, providing another example of spatiotemporal sedimentation in light. In this case the system is again not spatially connected (or gravitationally bound) — and the dynamics of its different parts (different gas clouds in this case) could be completely unconnected causally.

Dark Sector of the Universe

One of the most puzzling modern discoveries is that the observable components of the Universe (such as stars and galaxies) constitute only about 5% of the content of the Universe. The other almost 95%, which only interact with the observable parts of the Universe gravitationally, and due to their lack of interaction with electromagnetic waves cannot be seen, are referred to as dark. This dark sector of the Universe is composed of about ~ 27% dark matter and ~ 68% dark energy[8]. Even though their true natures are not understood at present, they appear to have very different natures and properties. Whereas dark matter is distributed unevenly and capable of acting locally to impact the dynamics of Galaxies, as well as providing a gravitational scaffolding for large cosmic structures, dark energy is thought to be distributed evenly in the Universe, acting globally to drive the accelerated expansion of the Universe. However, given our lack of understanding of their true natures it is at present not possible to know their sedimentary natures, if any.

Life as sedimentary

Another novel example of sediments is provided by the evolutionary processes

[7] Lynds, R., `The Absorption-Line Spectrum of 4C 05.34', *The Astrophysical Journal*, 164, 1971, L73 – L78. For an animation see: https://astrobites.org/2013/07/14/astrophysical-classics-neutral-hydrogen-in-the-universe-part-1/

[8] Aghanim, N., et al. `*Planck* 2018 results - VI. Cosmological parameters', *Astronomy & Astrophysics*, 641, 2020, A6.

and the biochemical and genetic structures of life forms. A key driver of evolution is random mutations which may or may not be selected by the organism and encoded in its genetic makeup. In fact the environment can impact the selection or deselection of particular parts of genes. In that sense the genetic makeup of organisms can be viewed as sedimentary, encoding selected mutations. But due to the complex nature of biological evolution with its complex interactions with the environment its sedimentary nature is far from being linearly accumulative, but instead likely to be far more complex by also including subtractive features, as for example in cases where evolution leads to shortening of RNA.[9]

Another interesting example, at least as far as our species is concerned, is provided by the evolution of language which could be viewed as sedimentary through a process of adaptations for complex vocalisations which themselves were fossilised in bones.[10] This is supported by fossil remains as well as recent data regarding the evolutionary history of some human DNA sequences, that have been classified in relation with hominid articulatory and auditory abilities.[11]

SEDIMENT AS A METAPHOR

The concept of Sediment has also been employed as a metaphor to discuss various aspects of human culture and history, including material, cultural, socio-historical and conceptual. Below we consider some examples.

Social - Historical

As their first tools our ancestors began modifying (breaking, reshaping, carving, sculpting) already existing material sediments, such as stones, bones, wood, etc., to construct objects such as stone tools and arrows — and through these early practices and modifications (whether additive or subtractive or both) introduced further human induced sedimentary layers as well as additional temporalities upon the objects they produced.[12] This is also true of later construction of objects,

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[9] Spiegelman, S., Haruna, I., Holland, B., Beaudreau, G., Mills, D., `The synthesis of a self-propagating and infectious nucleic acid with a purified enzyme', Proc. Natl. Acad. Sci. U S A., 54(3), 1965, 919–927.

[10] Klein, R. G., `Language and human evolution', *Journal of Neurolinguistics*, Vol. 43, Part B, 2017, 204-221.

[11] Balari S, Benítez-Burraco A, Longa VM, Lorenzo G. `The fossils of language: What are they? Who has them? How did they evolve?' In: Boeckx C, Grohmann KK, eds. *The Cambridge Handbook of Biolinguistics*. Cambridge Handbooks in Language and Linguistics. Cambridge University Press, 2013, 489-523.

[12] See for example Kubler, G. (1962), *The shape of time*, Yale University Press

structures and shelters by our ancestors and our contemporaries employing transformed fossilised materials, with their own geological/biological sedimentary histories, such as stones, bricks, wood, metals, etc. All such constructions could therefore be viewed as doubly or multiply sedimentary.

Similarly, sedimentary concepts can be invoked in discussing material aspects of `writing' in history, whether in the form of painted signs/images in caves, or by carving or pressing as in Cuneiform or by the addition of layers of ink in traditional and modern writing — or in modern data storage.

More interesting is the intriguing idea that our visual system has evolved to be good at seeing the structures we encounter in nature and that culturally our letters and symbols were developed to mimic these structures.[13] In that sense we could say that the shapes of signs and alphabets in different cultures carry sedimentary memories/reflections of the natural environment.

The concept of sediment has also been used as a metaphor in the conceptualisation of very different aspects of the developments in human history and culture, as for example in thinking of race in terms of sedimented history,[14] — or in exploring the relation between architecture and historical landscape formation.[15] Geological metaphors have also been used to describe historical knowledge, specially in phenomenological studies.[16] Examples include the so called sedimentation theory of cultural space and time[17], which employs and expands on Foucault's metaphor of archeology of knowledge[18], where time is envisioned as the accumulation of social practices layered in cultural space, and hence the present as embedded in the cultural past.

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[13] Changizi, M. A., Zhang, Q., Ye, H. and Shimojo, S., `The Structures of Letters and Symbols throughout Human History Are Selected to Match Those Found in Objects in Natural Scenes', *The American Naturalist*, vol. 167, no. 5, 2006.

[14] Ahmed, S., `Race as sedimented history', *Postmedieval: a journal of medieval cultural studies*, 6, 2015, 94–97.

[15] Sediment, issue 11, Room One Thousand, 2023.

[16] See e.g. Rump, J.M., `History as Soil and Sediment', *Danish Yearbook of Philosophy*, Vol. 48–49, 2013–2014, 139–152.

[17] St. Clair, R.N., `The sedimentation theory of cultural time and space: the present in embedded in the past', *CÍRCULO de Lingüística Aplicada a la Comunicación (clac)*,31, 2007, 52-90. See also Wei Song, St. Clair, R.N. and Song Wang, `Modernization and the Sedimentation of Cultural Space of Harbin: The Stratification of Material Culture', Intercultural Communication Studies XVII: 1, 2008, 22-37.

[18] Foucault, M. (1972), *Archaeology of Knowledge*, Pantheon Books, New York.

Sediments in art

All artworks are produced through creative processes which are dynamic in nature and include both conceptual and material aspects, which are nonlinearly intertwined, each possessing sedimentary features. The sedimentary nature of material aspect of works of art is transparent in the case of plastic arts, as in painting and sculpture, which not only employ materials which themselves possess earlier (cosmological and geological) sedimentary histories, but are also applied in sedimentary manners such as successive applications (additive) or removals (subtractive) of layers of paint and or other materials, or combinations of both. This is similarly the case with various forms of printing and graphic art, where layers of paint is applied in succession - as well as in etching, whose plates are often produced by removing layers (subtractive) and printed through successive (additive) applications of layers of paint. And the paints themselves, for example, are produced through the sedimentary (dispersive) mixtures of other paints and/or materials, etc.

Another interesting example is the so called Land/Earth arts, which employ the accumulation, removal, rearrangement and transformation of already existing natural/geological materials in landscapes. In that sense they are multiply sedimentary.

This is also the case with optical images and photographs which as was discussed above can be viewed as sedimentary — as is the case with films which could be looked upon as multiplicity of optical images, with an added nonlinear temporality introduced by layering and sequencing the images through editing. Similarly, music too can be viewed as sequences of and accumulation of sound waves in time.

Even conceptual art is produced through creative mental processes which are sedimentary, as are their materialisations, if they involve any.

I end this section with a poetic/metaphoric description of the interaction of material and mental processes involved in the production of works of art given by Robert Smithson, a key pioneer in the Land Art movement:

> `The earth's surface and the figments of the mind have a way of disintegrating into discrete regions of art. Various agents, both fictional and real, somehow trade places with each other—one cannot avoid muddy thinking when it comes to earth projects, or what I will call "abstract geology." One's mind and the earth are in a constant state of erosion, mental rivers wear away abstract banks, brain waves undermine cliffs of thought, ideas decompose into stones of unknowing, and

conceptual crystallisations break apart into deposits of gritty reason'.[19]

It should be noted, however, that despite their sedimentary natures, social and historical structures, as well as works of art, do not often preserve information/memory about their processes of creation and the extent to which they do so depends on the particular cases considered. What we are often left with is partial information about their sedimentary trajectories, or at times only their end results without the historical processes that gave rise to them being fully manifest.

Conceptual constructs

Another important use of the concept of sedimentation as a metaphor is in characterising the processes involved in certain theoretical disciplines. A key example is given by Husserl in his *Origin of Geometry*[20], in which he employs the metaphor of sedimentation to describe the processes through which abstract theoretical concepts in Geometry arise.[21] Starting from experimental observations and intuitive knowledge, he argues geometrical concepts arise through a gradual historical process of abstraction to final *stable* results, which due to their stability they can be communicated unchanged across space and time. He is, however, aware that the historical processes that led to such stabilised concepts involved the forgetfulness of the experiential processes that led to them in the first place — hence he refers to such Janus-faced dialectical process between discovery and forgetfulness sedimentation.[22] One could similarly perceive the subsequent developments in Geometry, and more generally in Mathematics as sedimentary, as we shall see below.

The importance of geometrical and more generally mathematical concepts treated as sedimentary is that, unlike material sediments which invariably change and wither, they seem permanent and invariant. In that sense they seem to belong to the category of what he refers to as ideal objects.[23] They are therefore unlike

[19] Smithson, R., `A Sedimentation of the Mind: Earth Projects', *Artforum*, 1968, 44–50.
[20] Husserl, E., 1989, *Origin of Geometry*, University of Nebraska.
[21] Geniusas, S., `The origins of sedimentation in Husserl's phenomenology', *European Journal of Philosophy*, 2024,1-17.
[22] Blomberg, J., `Interpreting the concept of sedimentation in Husserl's Origin of Geometry', Public Journal of Semiotics, 9(1), 2020, 78–94.
[23] In the sense of Platonic forms that are not subject to change.

all other material sediments in the Universe, in the sense that even though they arise historically (and are hence past-historical), they seem to be future-eternal (ahistorical).

It is interesting to note that similar to geometrical and mathematical concepts, scientific laws can also be treated as sedimentary. There is however a major difference between them, in that even though they are both past-historical, scientific laws are in principle open to change and are hence also *future historical.*

KEY POINTS RAISED

Our generalised definition of sediments has allowed a large number of processes and structures to be viewed as sedimentary, and has in turn highlighted some important features regarding the nature of sediments in the observable Universe. In the following we shall briefly discuss some of these.

Enormous variety

Above considerations have shown that sediments can have very diverse natures and forms. These include: sediments in geological settings (layered); sediments in gaseous/plasma settings (dispersive, non-layered); sediments with cataclysmic phases; sediments with manifestly spatiotemporal nature and sediments in historical and conceptual domains.

Multiple origins

Viewed from a cosmological perspective, sediments generally possess multiple origins. In the case of physical, chemical, biological and field sediments this is clear, given that they all are made of matter or energy, themselves possessing sedimentary natures with multiple origins that lie deep in the past history of the Universe. This is readily seen in the case of geological sediments, where the rocks we see are descendants of multiple generations of earlier rocks raised from the depth of the Earth by convective processes, some eventually washed into fine sands through erosion before being laid back into the depth of oceans to form the next generation of rocks after tens of millions of years of compression. And in turn the heavier atoms constituting such sediments themselves produced cataclysmically in earlier generations of stars, etc. Thus looking at sediments from a cosmological perspective highlights the fact that their *origins are always multiple.*

Importantly, this is also likely to be true in the case of historical, social, artistic and conceptual sediments.

Relation to time and stability

As outcomes of dynamical processes, sediments are intimately tied up with time. This relationship is, however, far from being a simple or a linear one. There are many reasons for this temporal complexity, among them: the interactive and nonlinear (including chaotic) processes involved in the production of sediments, as well as their multiple origins, each with their own temporalities. Time also plays important roles in distinguishing between different classes of sediments: by the way they encode time as well as the length of their lifetimes. As we have seen different classes of sediments encode time very differently: explicitly (in layered sediments), implicitly (in dispersive sediments), and implicitly with ruptures (in cataclysmic sediments). And they can possess an enormous range of lifetimes, including those with lifetimes enormously longer than the present age of the Universe (s.a. low mass stars), and still others that appear to be future eternal (Mathematics).

An interesting related question concerns the stability of sediments, i.e., the time scale of their perseverance. One could in principle define two notions of stability: relative and absolute, with the former indicating the perseverance of a sediment relative to the lifetime of a particular observer, and the latter indicating stability for all times. In above examples only the geometrical/mathematical sediments are thought to possess absolute stability. The question becomes what happens to the ultimate fate of material and field sediments in general, in a transient Universe? We shall briefly return to this question below.

HOW IS OUR CONCEPTION OF SEDIMENT ENRICHED?

We may ask how can the above considerations enrich our conception of sediments? To explore this question we shall consider some examples.

Development of Geometry and Mathematics

As our first example consider the development of Geometry as sedimentary, as considered by Husserl. Our discussions above provide a number of important additional insights, including the fact that the prehistory of Geometry, like all sediments, possesses multiple origins, including contributions by earlier cultures predating Euclid's formalisation of such knowledge culminating in Euclidean Geometry (with its 6 axioms, including the so called Parallel Axiom) around 300 BC. More importantly, our considerations indicate that a simple accumulative layered geological picture is not appropriate as a sedimentary metaphor to account for the longer term evolution of Geometry, including its modern developments. In fact Euclid's axiomatic development (and in particular his Parallel Axiom) can be viewed as an important stage in the sedimentary process of development of Geometry whose coming to be impacted (and effectively stifled) the wider development of Geometry for over two millennia. Furthermore, to account for the rupture that the abandoning of the Euclid's Parallel Axiom caused (which amounted to the breaking of an effective conceptual block that had survived for over two millennia)[24], a more appropriate sedimentary metaphor would be one which included subtractive/additive cataclysmic phases (with metaphoric parallels with sedimentary processes involved in the evolution of massive stars with their supernovae explosions) resulting in qualitatively new sedimentary structures — in this case the novel Non-Euclidean geometries. Developments which in turn proved fundamental in the birth of key new scientific theories in early 20th C, and in particular Einstein's general theory of relativity, that enabled our modern conceptualisation of the Universe — theories that themselves can be viewed as sedimentary.

Similar to Geometry, the origin and development of Mathematics can also be viewed as sedimentary. To do so, it is instructive to recall that there are a number of different philosophical positions concerning its nature, including whether Mathematics is constructed by us or is out there, given in a platonic sense, independently of us. Among —those holding the former position are those that take a cognitive neuroscience perspective according to which Mathematics is an outgrowth of our cognitive apparatus which is in turn conditioned by the world in which our ancestors have evolved. From this perspective, and on the basis of experiments and observations, it has been argued that during the course of the evolution our primate brain has evolved an elementary ability to represent certain aspects of the external world, which include a so called *number sense*, i.e., an

[24] Despite the great deal of effort made over the centuries by mathematicians in many parts of the world to prove the derivability of the Parallel Axiom from the other axioms.

inherited ability to approximate quantities.[25] This ability is shown to be shared with groups of other animals. Given this ability, the key question then becomes where did the precise (non-approximate) sense of numbers, and more abstract Mathematics, come from? There are a number of different positions regarding this fundamental question. According to one, and relying on research showing that human infants develop a precise sense of numbers by the age of 3 or 4, it is argued that this precise sense, which does not seem to be shared by other animals, is facilitated by language. According to this view the development of Mathematics is an outcome of our cultural development and abstract abilities of our minds.[26] Others, on the other hand, argue that the precise number systems and arithmetic were developed culturally in recent human history, independently of natural selection. In that sense they believe number systems are neither hard wired nor are they out there independently of us to be discovered.[27] Rather, they emphasise the combined role of non-mathematical everyday cognitive mechanisms that make human imagination and abstraction possible, with emphasis on the role of conceptual metaphor.[28]

Despite the important differences between these positions, we could say that in all cases the key processes involved in the development of Mathematics, both biological and cultural, are sedimentary. Even if one takes a platonic position regarding its origin — the process of its discovery is still sedimentary.

Again we may ask what type of sedimentary metaphor would be more appropriate to conceptualise the developments in Mathematics? The above considerations suggest that rather than a simple (layered) geological picture, a more appropriate sedimentary metaphor, would be one which possesses multiple origins, both biological and cultural, with the new developments in different branches of Mathematics evolving differently through contributions and interactions between different authors at different locations in the world, at

[25] Dehaene, S., 1997. *The number sense: How the mind creates mathematics*, Oxford University Press.

[26] Shepard, R., `Perceptual-cognitive universals as reflections of the world', Behavioral and Brain Sciences 24, 2001, pp. 581–601. See also Dehaene, S., Piazza, M., Pinel, P., Cohen, L., `Three parietal circuits for number processing', *Cognitive Neuropsychology*, 20, 2003, 487–506.

[27] Nunez, R., `Numbers and Arithmetic: Neither Hardwired Nor Out There', *Biological Theory*, 4(1) , 2009, 68–83.

[28] Lakoff, G; Nunez, R., 2000, *Where Mathematics Comes From: How the Embodied Mind Brings Mathematics Into Being*, New York: Basic Books.

different times and at different rates. Thus the accumulated mathematical knowledge at any given epoch can be viewed as a spatiotemporal sedimentary tapestry in formation, with each point of which formed at a different place and at a different time.

Again such developments are not necessarily always smooth, but could include cataclysmic phases. A interesting example is provided by the collection of key mathematical results (which could be viewed as sediments) around mid 20th C, culminating in the important realisation that simple nonlinear mathematical deterministic systems can produce extremely complex (chaotic) behaviours — resulting in a key paradigm shift: that complicated dynamical behaviour does not necessarily require a complicated underlying mechanism, or a breakdown of determinism.

Carbon Cycle

As our second example consider the important case of the Carbon Cycle, which denotes the movement and circulation of Carbon (one of the most abundant elements on Earth) between the key components of our terrestrial environment: the atmosphere, the oceans, the biosphere and the Earth's crust. Being effectively a closed system, the circulation of Carbon between different parts of the terrestrial environment can change its concentration in its different parts while maintaining its overall size. This is important given that Carbon plays a key role in maintaining life on Earth, as well as its crucial role in maintaining the Earth's climate by controlling the concentration of carbon dioxide in the atmosphere.

The processes involved in the circulation of the Carbon reservoir between these components are complex and yet sedimentary, taking very different forms and time scales. For example, the burning of fossil fuels has led to an alarming increase in carbon dioxide in the atmosphere, which can be looked upon as a dispersive form of sedimentation in the gaseous atmosphere with its mixing properties. The concentration of carbon dioxide in the atmosphere is in turn impacted by its interaction with the upper layers of oceans through absorption, which again could be treated as a sedimentary process. Carbon can also be transported to deeper layers of oceans by being mixed with material sediments that are washed into the oceans, as well as by small organisms such as Phytoplankton that absorb carbon dioxide near the surface layers and sink to the deep oceans at the end of their lives, where in time they are re-mineralised and together with other sediments get buried and turn into geological type sedimentation with far longer time scales. There is also the exchanges of Carbon between the biosphere and atmosphere through photosynthesis, respiration and fossil fuel burning. In this case the carbon dioxide is absorbed in the biosphere through layered biological sedimentation in forests (in the form of tree rings) as well as in shells, whereas its increase in the atmosphere is through a dispersive sedimentary process. There are also important feedback mechanisms operating in this nonlinearly coupled system, such as how the increase of the carbon dioxide in the atmosphere with the subsequent temperature increases in the atmosphere and the oceans can decrease the efficiency of oceans to absorb the atmospheric carbon dioxide.

This very short summary demonstrates the role played by various forms of sedimentary processes in the very complex dynamics of the Carbon Cycle with its crucial importance for our survival.

Anthropocene

Another important related example is that of so called Anthropocene[29], i.e., the onset of the epoch starting with the industrial revolution, but more specially since the 1950s, in which the Earth and all its components including its climate, oceans, etc., have been significantly impacted by human activities. These major human impacts could be viewed as ongoing and alarmingly accelerating sedimentary processes. In this case the sedimentary processes are again multiple, ranging from geological type sedimentation during say the deposition of nuclear particles, waste plastics and other pollutants in soil, and subsequently future geological sediments, to increasing pollutions in the oceans and the atmosphere which can be treated as dispersively sedimentary, as discussed above. In fact it has been argued that human action now dominates the sediment cycle — i.e. the mobilisation, transport and sequestration of sediments on the global scale.[30]

[29] Raupach, M. R., Canadell, J. G., `Carbon and the Anthropocene', *Current Opinion in Environmental Sustainability*, 2 (4), 2010, 210-218.
[30] Syvitski, J., Ángel, J. R., Saito, Y. et al. `Earth's sediment cycle during the Anthropocene'. *Nature Reviews, Earth & Environment, 3, 2022,179–196.*

FATE OF THE SEDIMENTS IN A TRANSIENT UNIVERSE

As was mentioned above, one of the most profound modern findings about the Universe is that it is dynamic and expanding. As a result the very far future and the possible fate of the Universe have been the subject of a great deal of study and speculation but remain uncertain due to a number of fundamental unknowns. For example, according to the current cosmological observations the Universe is very nearly flat and accelerating. Assuming the Universe to be truly flat, as it is often done in the so called standard model of cosmology, and depending upon the nature of the dark energy, the Universe could keep on expanding forever and hence be transient. There are, however, major unknowns that could change this outcome. These include whether our current assumptions in formulating cosmology are correct and will continue to hold for all future times, and importantly whether the currently known laws of physics will remain unchanged indefinitely?

If the above assumptions turn out to be correct, then in such a truly transient Universe all its sediments with finite lifetimes must ultimately decay, however long their lifetimes. The key question becomes what happens to components of the Universe that at present seem to be stable with seemingly unlimited lifetimes, such as for example protons and photons?

Despite the above mentioned uncertainties, a number of studies have been made of the very far future fate of the Universe.[31] As we move very far into the future the underlying physics becomes more and more uncertain, in part due to the uncertainties regarding the particle physics in such epochs. For example, at present there is no evidence to suggest that protons are unstable and will decay in finite time, with the current studies indicating that they have a minimum lifetime of at least 1.67x1034 years.[32] If protons were to be unstable on still longer time scales then all atomic nuclei in the Universe, and with them all material structures and sediments, would eventually decay. Another important ingredient of the visible Universe is photons. Again it is at present not known whether photons remain stable on extremely long time scales.[33] Similarly the fate of the

[31] For a review see Adams, F. C., Laughlin, G., `A dying universe: The long-term fate and evolution of astrophysical objects', *Reviews of Modern Physics*, vol. 69, 1997, 337–372.

[32] See e.g. Davoudiasl, H., Denton, P. B., `How fast can protons decay?', *Physical Review D*, 111, 2025, 035026.

[33] See e.g., Heeck, J., `How Stable is the Photon?', *Phys. Rev. Lett.*, 111, 2013, 021801.

dark matter and dark energy are not known. Taken together, these uncertainties and unknowns, imply that the nature and the fate of the very far future of the Universe is uncertain at present.

And finally there is the important question regarding the fate of the conceptual sediments such as Mathematical concepts, which seem to be absolutely stable, in a transient Universe. The answer to this question depends on our philosophical position regarding the nature of Mathematics itself. Assuming that mathematical concepts were invented by us would imply that they would ultimately perish in a transient Universe, if and when we (and all intelligent life in the Universe that share such knowledge) wither away. On the other hand, if mathematical facts exist independently of us, then the question becomes how and when did they appear? Were they created with the Big Bang? And what happens to them in the far future of a transient Universe?

CONCLUSION

An important outcome of our more generalised way of looking at the concept and metaphor of sediment discussed above is to provide a broad enough framework to view the enormously diverse range of outcomes of dynamical processes in the observable Universe as sedimentary, in both terrestrial and extra-terrestrial domains.

This new framework has also highlighted the fact that sediments in the observable Universe are in general dynamically active, non-fossilised and occur in settings far more varied and different from the geological ones, including liquid, gas/plasma, field, as well as biological, social, historical and conceptual settings. And that in general such sediments can be layered as well as non-layered and dispersive — accumulative or subtractive, or a combination of these. They include sedimentary structures which are non-localised and spatially unconnected, making them manifestly spatiotemporal, often with parts that are causally independent of one another; as well as others that are in principle closed to observers, such as black holes. It has further shown a number of key features that sediments share in general. In particular, the fact that their origins are in general multiple, and importantly that their dynamical becoming can impact the processes giving rise to them. These include classes of sediments that in the course of their evolution go through cataclysmic metamorphoses (as in the case of massive stars) during which they can also radically and irreversibly change the environments that gave rise to them, before settling down into qualitatively different forms of sedimentary structures.

The above discussions have also demonstrated that an important way to categorise the variety of sediments in the observable Universe is through the way they relate to time. This concerns not only the vast range of lifetimes that they can possess, including sediments with lifetimes enormously longer than the present age of the Universe, as well as those that appear to be future eternal. But importantly also the different ways sediments can encode time: explicitly (as in layered sediments), implicitly (as in dispersive sediments), and implicitly but with ruptures (as in cataclysmic sediments).

This more generalised way of looking at sedimentary processes also enriches the metaphor of sediments applied to conceptual and historical processes by providing important new insights. For example, the fact that sediments possess multiple origins widens our perspective on how to conceptualise the developmental processes and genealogies of historical and conceptual constructs viewed as sediments. Similarly the possibility of cataclysmic metamorphoses in sedimentary processes can provide insights into rethinking the future possibilities of ruptures in the developments of historical and conceptual processes.

And finally, by emphasising the dynamical and nonlinear nature of sedimentary processes, as well as the interactions between them, it indicates the potential presence of chance and contingency in such processes which in turn hints at how they could have resulted in very different trajectories and outcomes in both natural as well as socio-historical[34] and conceptual sediments.

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[34] For a possible alternative trajectory that human history could have taken, see Graeber, D. and Wengrow, D., 2021, *The Dawn of Everything: A New History of Humanity*, London: Penguin/Allen Lane.