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THE ROCK CYCLE OF THE ANTHROPOCENE: INSERTING HUMAN AGENCY INTO THE EARTH SYSTEM

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ABSTRACT

The Rock Cycle, or Geological Cycle concept, represents an ideal model for the formation of new geological materials from pre-existing geological materials, and has been extensively studied and used for teaching and the dissemination of Geosciences throughout decades. However, the "cycles" shown in publications and textbooks fail to take into account the human geological agency, the importance of which has recently been widely recognized. This work justifies such consideration and suggests a Geological Cycle model incorporating processes and geological materials produced by humanity that characterize the Anthropocene.

Keywords: Geological Cycle; Rock Cycle; Anthropogenic Rocks and Grounds; Anthropocene.

RESUMO

O CICLO DAS ROCHAS DO ANTROPOCENO: INSERINDO A AGÊNCIA HUMANA NO SISTEMA-TERRA. O conceito de Ciclo Geológico, ou Ciclo das Rochas, representa um modelo ideal de formação de novos materiais geológicos a partir de materiais geológicos preexistentes, e tem sido extensamente estudado e utilizado para a finalidade do ensino e divulgação das Geociências, ao longo de décadas. Todavia, os "ciclos" presentes nas publicações e livros-textos deixam de levar em consideração a atividade geológica humana, cuja importância tem sido amplamente reconhecida recentemente. Este trabalho justifica tal consideração e sugere um modelo de Ciclo Geológico incorporando processos e materiais geológicos produzidos pela humanidade que caracterizam o Antropoceno.

Palavras-chave: Ciclo Geológico; Ciclo das Rochas; Rochas e Terrenos Antropogênicos; Antropoceno.

1 INTRODUCTION

Although ideas concerning cyclical processes have meaningful significance in the history of Earth Sciences, such as in the Hutton's sedimentation cycles (GOULD 1991, GREGOR 1992), in the geomorphologic evolution model of Davis' "Geographic Cycle" (1991) or in Holmes' tectonic cycle (HOLMES 1952) and its refined version by Plate Tectonics (the "Wilson Cycle"), nowadays the concept of Geological Cycle, or Rock Cycle, also referred to as Rock Transforming Cycles, or even Geochemical Cycle, also appears as a conceptual tool commonly used in didactic terms, in textbooks of Geosciences and Environmental Sciences used for higher education studies (e.g. FOSTER 1966, ROGERS & ADAMS 1966, MASON 1971, ERNST 1988, STRAHLER 1992, WALTHAM 1994, THE OPEN UNIVERSITY 1994, VAN ANDEL 1994, LUTGENS & TARBUCK 1995, MERRITS et al. 1997, ERNST 1999, LUNINE 1999, TEIXEIRA et al. 2000; SANTOS 2002,

LUTGENS & TARBUCK 2005, MARSHAK 2005, PRESS et al. 2006, MERALI & SKINNER 2009, TEIXEIRA et al. 2009, WICANDER & MONROE 2009, HUDDART & STOTT 2010, ALBARÈDE 2011, DAS 2011, LEPSH 2011, MILLER 2011, SKINNER & MURCK 2011, SGARBI 2012, TARBUCK et al. 2012, TORRES et al. 2012, TEIXEIRA 2014, BOUROTTE 2014).

The theme has also been approached often for decades in articles that bring conceptual discussions or pedagogical proposals and analysis concerning the educational use of the concept of Geological Cycle (*e.g.* BALDWIN 1962, SINGH AND BUSHEE 1977, EVES & DAVIS 1988, GREGOR 1992, MAHER 1992, STOFFLET 1994, FICHTER 1996, KALI 2003, CARNEIRO & LOPES 2007, CARNEIRO et al. 2009, LOPES AND CARNEIRO 2009, SCHIFMAN et al. 2013), or even for the popularization and dissemination of science among non-specialists (AGUIAR 2004, SCHUMANN 2008, SCLIAR 2009, ANDRADE 2011, CRIST & PINTO 2014).

However, in all the cited productions, in which the Cycle's graphic representation appears in an almost detailed form, with variations pertinent to the objectives of the publication, there is always a significant lapse: the absence of consideration of the human geological agency and their products and records. These themes, on the other hand, have been treated in the geological and natural sciences literature since the nineteenth century and the beginning of the twentieth century, and in Brazil such studies have been systematically carried out from the beginning of the 1990s, from the concepts of "technogenic deposits" and "Technogene" or "Quinary" Periods proposed by Soviet Engineering Geology (CHEMEKOV 1983; TER-STEPANIAN 1983, 1988, 1994), and subsequently incorporating categories from British Geology (*e.g.* McMILLAN & POWELL 1999; ROSEMBAUM et al. 2003; PRICE et al. 2004, 2011; see also reviews by OLIVEIRA et al. 2005, PELOGGIA 2005, PELOGGIA et al. 2014, PELOGGIA & ORTEGA 2016, FRANÇA et al. 2018).

This lack of consideration for human geological activity in such a meaningful concept in pedagogical terms, especially that of the Rock Cycle as represented in textbooks, has become particularly striking in recent years, when, the international scientific community officially discussed the creation and the stratigraphic status of the Anthropocene, a concept proposed in the 2000s to characterize contemporary geological time, in which human agency had become recognized as significant on the surface of the Earth, including the biosphere (e.g. CRUTZEN & STOERMER 2000; CRUTZEN 2002a, b; STEFFEN et al. 2007, 2011, 2016; ZALASIEWICZ et al. 2008, 2010, 2011a, b, 2017; RUDDIMAN 2013; GIBBARD & WALKER 2014; OLIVEIRA & PELOGGIA 2014; WATERS et al. 2014, 2016; LEWIS & MASLIN 2015; RUDDIMAN et al. 2015; WILLIAMS et al. 2016).

It should be noted that, although the formal definition of the Anthropocene as a chronostratigraphic - geochronological unit is still an issue in full debate, the discussion has not revolved around accepting the concept of Anthropocene itself, but defining (or not) a stratigraphic (temporal) limit for its beginning. Regardless of this controversy, it is clear that the concept of Anthropocene (or Anthropocene *sensu lato*, which is what we use here) has become widely accepted and used, not only among scientists, but in the cultural common sense (*e.g.* MARTINI & RIBEIRO 2011, AUTIN & HOLBROOK 2012, ARTAXO 2014, ZOLNERKEVIC 2016, ZALASIEWICZ 2016, BOSTIC & HOWEY 2017, TRISCHLER 2017, CEARRETA 2017, BAUER & ELLIS 2018, ZALASIEWICZ et al. 2018)

In this context, it becomes evident, the need for research and teaching purposes, to review and update the Rock Cycle concept, incorporating, along with natural geologic processes and materials, those of anthropogenic nature. Given that the concept being dealt with is an ideal construction, in which the possibility of forming geological materials from other preexisting materials is posed, and in which all geological processes fit in, there is no point in disregarding the processes and records of human agency. In this paper, we present a proposal based on the model suggested by CATHCART (2011), formulated from UNDERWOOD (2001a, b) propositions, and from the changes suggested by FORD et al. (2014).

2 NATURAL ROCK CYCLE MODELS

Before we turn to the question of updating the concept of the Geological Cycle taking into account the human agency, it is interesting to verify its previous pedagogical use in textbooks and similar publications, which considers only

"natural" processes, excluding human agency and its products.

There are basically two types of representations of the Geological Cycle in the literature listed above, a sample restricted internationally but reasonably broad in respect of what was published in Brazil (Figure 1): the first one identified as Type 1 consists of simple (Type 1A) or illustrated (Type 1B) "boxes and arrows" schemes, and the second (Type 2) corresponds to schematic-figurative representations ("concepts and arrows") produced over a background design that represents the diversity of geological contexts in which the formation of geological materials is processed, from the deep crust or even the mantle to the atmosphere. In table 1 we present a synthesis of the Cycle models as viewed in the studied publications.

In fact, the two categories have the same basic configuration, closed loop, varying only in detail: compartments (boxes), representing different geological materials (and, implicitly, constituting "reservoirs" of these materials), connected by arrows, indicative of processes that allow the transformation of matter between geological categories, in a clear geological explanation of Lavoisier's principle that nothing is created or lost but all transformed.

Variations of the basic model can occur in the form, for example, of representation of the position of the terrestrial surface (boundary lithosphere/ atmosphere - hydrosphere), differentiation of crustal and mantle circuits, parallel sub-cycles (representing biosphere processes), reference to tectonic environments, reservoirs and flows with representations in proportional sizes, geochemical emphasis (reservoirs and flows of elements), geotectonic settings etc..

In summary, for decades the basic model of the rock cycle has been used in textbooks without significant variations in its essence. It is true that in the older texts the Type 1A scheme predominates, whereas in the more recent publications, which have further advanced graphic features, types 1B and 2 tend to appear more frequently. It is therefore a consolidated concept**,** and it is from its simplest version (Type 1A) that we will discuss the particularities of the new geological cycle of the Anthropocene.

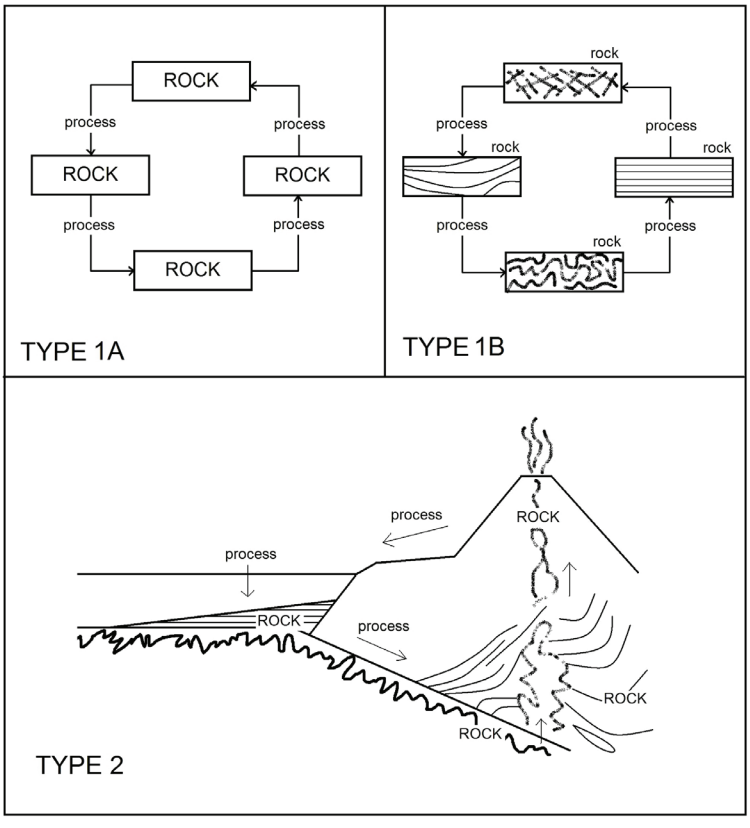

FIGURE 1 – Most common Geological Cycle graphic patterns.

TABLE 1 – Examples of use of the Geological Cycle in geoscientific didactic publications, organized by date from the 1960s to 2010s.

Reference	*Type*	*Publication Category*
Rogers & Adams (1966)	1 A	Textbook of Geology
Foster (1966)	1 A	Textbook of Geology
Mason (1971)	1 A	Textbook of Geochemistry
Ernst (1988)	1 A	Textbook of Geology
Strahler (1992)	1 A	Textbook of Physical Geography
Waltham (1994)	1 A	Textbook of Engineering Geology
Van Andel (1994)	1 A e 2	Textbook of Environmental Geology
The Open University (1994)	2	Textbook of Economic Geology
Lutgens & Tarbuck (1995)	1 B	Textbook of Geology
Merrits et al. (1997)	1 A e 1 B	Textbook of Environmental Geology
Ernst (1999)	1 B	Textbook of Environmental Geology
Lunine (1999)	2	Textbook of Geology
Madureira et al. (2000)	1 B	Textbook of Geology (chapter)
Santos (2002)	1 A	Textbook of Engineering Geology
Aguiar (2004)	2	Scientific popularization text
Lutgens & Tarbuck (2005)	1 B	Textbook of Geology
Marshak (2005)	1 B e 2	Textbook of Geology
Press et al. (2006)	1 B	Textbook of Geology
Schumann (2008)	1 A	Scientific popularization text
Andrade et al. (2009)	1 A e 2	Textbook of Geology (chapter)
Wicander e Monroe (2009)	2	Textbook of Geology
Scliar (2009)	1 B	Scientific popularization text
Merali & Skinner (2009)	1 B	Textbook of Geosciences
Huddart & Stott (2010)	2	Textbook of Geology
Albarède (2011)	1 A	Textbook of Geochemistry
Andrade (2011)	1 A	Scientific popularization text
Lepsh (2011)	1 B - 2	Textbook of Pedology
Miller (2011)	1B - 2	Textbook of Environmental Science
Das (2011)	1 A	Textbook of Geotechnics
Skinner & Murck (2011)	1 B	Textbook of Geosciences
Sgarbi (2012)	1 A	Textbook of Geology (chapter)
Torres et al. (2012)	1 A	Textbook of Geomorphology
Tarbuck et al. (2012)	1 B	Textbook of Geology
Crist e Pinto (2014)	1 A	Scientific popularization text
Teixeira (2014)	1 A	Textbook of Geology (chapter)
Bourotte (2014)	1 B	Textbook of Geology (chapter)

3 THE NATURAL - ANTHROPOGENIC CONCEPTION OF THE GEOLOGICAL CYCLE

CATHCART (2011), based on the propositions of UNDERWOOD (2001a, b) on the "fourth basic class" of rocky materials, elaborates a scheme of the Cycle in which are identified the "anthropic rocks", by means of a single "box", and the anthropogenic processes which may lead to their production, represented by "arrows". In figure 2 we present the version of this cycle with the modifications suggested by FORD et al. (2014).

In this proposal, anthropic rocks (eventually called artificial, synthetic, technogenic or even "pseudo-rocks") have the following peculiarities: they result from processes which may be observed and are well understood, are composed of materials from local sources or transported over large distances, have a large volume of production and, once produced, can also be used locally or transported (UNDERWOOD 2001a).

Such new rocky materials, in the aforementioned classification, are formed by actual production, such as bricks, tiles, asphalt, concrete and glass, constituting the category of anthropogenic rocks (made by humans); by handling, by means of cutting, grinding, polishing etc., deriving the "antropotechnic" rocks (modified by humans); and by movement and replacement,

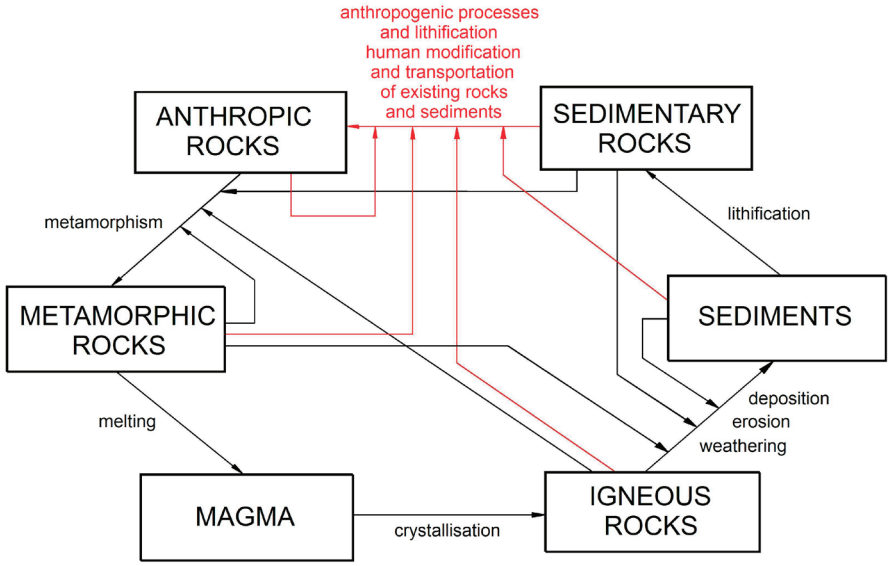

FIGURE 2 – Representation of Cathcart-Underwood's Geological Cycle conception, adapted from the modification proposed by Ford et al. (2014). The anthropogenic processes are indicated in red.

the "anthropokinetic" ones (moved by humans) (UNDERWOOD 2001b, CATHCART 2011). In the first case, manufacturing processes can be associated with "igneous" types, for instance glass or metals (derived from molten material), "metamorphic" (as a result of solid-state transformations such as bricks and ceramic materials) or "sedimentary" ones, in the case of concrete. The latter, the "most abundant type of new rock of the Anthropocene," can be classified as a "sandy conglomerate, poorly selected with carbonate cementation" (WATERS & ZALASIEWICZ 2018). In mineralogical terms, at least 208 "human-mediated" mineral-like species that occur mainly or exclusively as consequence of anthropogenic processes are officially listed (HAZEN et al. 2017), and it is possible to talk about a "mineral signature" of the Anthropocene (ZALASIEWICZ et al. 2014a). In this context, plastics also appear as significant materials in geological terms (ZALASIEWICZ et al. 2016).

However, we must consider that the human geological agency produces not only rocky materials, but also unconsolidated materials that refer to the categories of sediments and soils, that is, surficial formations (*sensu* CAMPY & MACAIRE 1989). In this sense, it should be convenient to add to the "box of the sediments" of the previous scheme the technogenic deposits and soils forming the artificial ground, indicating their specific processes of formation, namely: induced and accelerated erosion; excavation; technogenic deposition; modification of pre-existing soils. These processes, in essence, have led to the formation of the human geological stratum (ZALASIEWICZ 2008) or archaeosphere, understood as a "carpet layer" that encompasses all the humanly modified ground that has accumulated on the Earth's surface (EDGEWORTH 2014, 2016; PELOGGIA et al. 2017).

We can also include the process of incorporation of technogenic components (or technofossils) to non-technogenic soils and sediments, notably in the form of small metal particles, glass, plastics etc. (OSOVETISKIY 1996; MAXIMOVICH et al. 2000; ZALASIEWICZ et al. 2014b, 2016a; ZALASIEWICZ 2016; DAVIS 2016).

Also, for anthropogenic rocky materials, it may be of interest to indicate the occurrence of artificial structures, which would correspond by analogy to geological structures or formations. These elements are an important part of the active technosphere (HAFF 2014), notably in urban areas, but would not be incorporated into the human geological stratum, or archaeosphere, which as a stratigraphic record would correspond to the Antropocene Series (ZALASIEWICZ et al. 2016, 2017). Despite this, they are elements analogous to rocky structures "in production".

These modifications are proposed in figure 3 and encompass the totality of the technogenic geodiversity (PELOGGIA et al. 2014) that

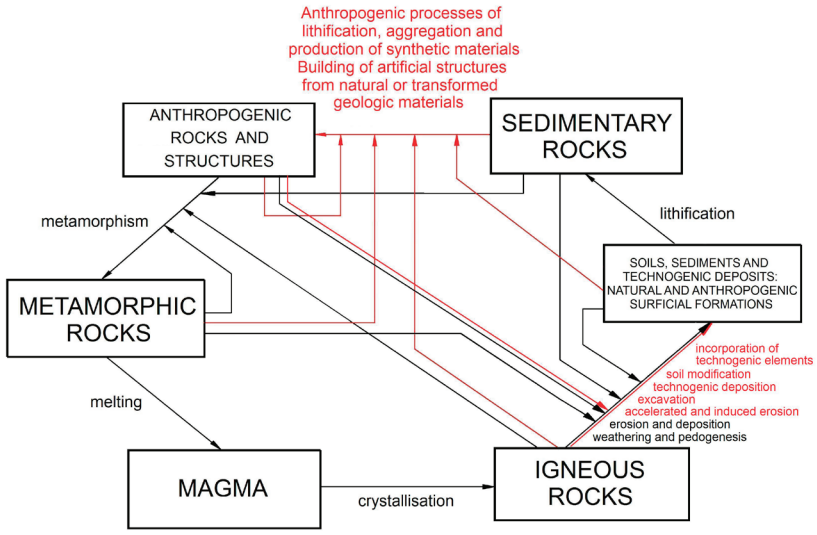

FIGURE 3 – Proposal of the Anthropocene Geological Cycle, considering rocky materials and anthropogenic deposits, with indications of related processes in red.

constitutes the artificial ground (WATERS 2018) and forms the "physical technosphere" (ZALASIEWICZ et al. 2017) in its residual part, but also refers to the processes that occur in the "active technosphere".

4 GEOLOGICAL PROCESSES AND EARTH SYSTEMS

It is evident that the geological processes represented in the natural geological cycles take place in real contexts or, rather, occur as part of the earth systems, whether related to internal dynamics (plate tectonics) or to external processes (erosion and deposition systems). This is best evidenced, even implicitly, in the "type 2" representations of the Cycle. In this sense, what we propose is basically the incorporation of a new geological system, the Humanized Earth System (HES), as proposed by RULL (2016), to the Cycle.

This new Earth System concept includes the processes, markedly of external geological dynamics, related directly or indirectly to the human agency, and can be understood as a set of sub-systems (technogenic systems) represented by characteristic geological processes and records, as proposed by FIGUEIRA (2007). The variety of technogenic systems, in a similar way to that of depositional systems, includes canals and reservoirs, mining grounds, residues deposition and urban occupation.

In this context, the urban technosphere and its processes, related to technogenic systems, seems to be the most evident, exemplary and significant expression of the part that is due to humanity in the Geological Cycle (EDGEWORTH 2016; ZALASIEWICZ et al. 2017, 2018; PELOGGIA et al. 2017).

5 FINAL REMARKS

UNDERWOOD (2001a) argues against the idea that rocks derived from human agency would not be natural, comparing the structures and constructions built by mankind to the great masses of coral reefs produced by complex communities of invertebrates, an analogy also proposed by PELOGGIA (1999). This idea certainly does not mean that human agency is qualitatively equivalent to the geological action of the invertebrates, but it points out that in both cases, there are comparable geological results. Fortunately, the most recent scientific literature has overcome the supposed "dichotomy" between humanity and nature, emphasizing the differentiation of one to another, with the production, in the end, of a nature transformed by the new agent whose geological representatives are the technogenic ground and strata.

Also fortunately, the reaction referred by ZALASIEWICZ (2016) to the pioneering propositions that emphasized the importance of the human geological agency, to which the geologists have no longer resorted to with any such kind of resistance, was also felt in Brazil, by the first researchers who widened the study parametres of the subject, then created under the concept of "Technogene", roughly the equivalent to that of Anthropocene.

However, as far as textbooks are concerned, as we have seen, the situation is essentially the same as that described 60 years ago by FELDS (1958, p.354), and generically extended to the entire field of Geosciences: "The Geomorphology textbooks do not deal with their part in the morphogenetic activity of man whose participation in facts and geomorphological evolution is therefore considerable." Such disregard by higher education textbooks contributes to a significant gap in the training of new geoscientists and teaching of geosciences to non-specialists, hampering the efforts that teachers may make to include the theme in their disciplines. In this context, UNDERWOOD (2001a) considers that if a basic objective of geological studies is to determine geological history, and if today this history can also be represented by anthropic rocks (and, remember ourselves, other technogenic formations), recognition and interpretation of this record and its formation processes may clarify a relevant part of the same story.

Otherwise, the "possibility of stories" condensed in the concept of the Rock Cycle and its representations will be without a decisive chapter if it does not include the anthropogenic materials and processes, implying this omission, as we argued, in significant educational loss, since a powerful tool for discussion and reflection will not be made available to teachers and students. The incorporation of this debate in the textbooks of geosciences represents an important step towards consolidating in teaching a theme that has shaken and also enhanced the geological thought, and had influence in the popular culture like few others.

After all, the new scheme of the Anthropocene Geological Cycle presented here represents a possibility, in fact a first approximation from the models usually used, and which can be improved, for example, from the full application of the concept of earth systems to the scheme.

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