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Hauling Data. Anthropocene Analogues, Paleoceanography and Missing Paradigm Shifts

Christoph Rosol [*]

Abstract: *»Daten heben. Geologische Entsprechungen zum Anthropozän, Paläoozeanographie und fehlende Paradigmenwechsel«*. The interdisciplinary study of paleoclimates is symptomatic of how the climate and earth sciences represent a matured practice of pragmatically dealing with purely heuristical strategies and implicit uncertainties. Both have not only become important providers of crucial data for decision making in contemporary societies but are also becoming role models for other sciences. To give an epistemic framework for this new prestige, the paper first focuses on three interconnected conceptual terms that are central to paleoclimatology: the earth itself as an *experimental* setting that has recorded deep-time climatic *events*, which could serve as geological *analogues* to assess the current rapid transition from the Holocene into the Anthropocene. In order to demonstrate the historical foundations of such a rationale, the paper then explores the history of proxy-data generation and analysis by focusing on the development of paleoceanography – a critical discipline in forming a deep-time perspective on climate history. By highlighting the technology-driven transformations of this field during the era of the great oceanographic expeditions and the start of stable isotope analysis in the aftermath of World War II, it argues for a strong historical continuity of the epistemic framework of paleoclimatology.

Keywords: Climate change, history of the earth sciences, computer modeling, proxy data, heuristic strategies of the earth sciences.

1. Introduction: A Conceptual Framework for Reflecting on Paleoclimate Science

The study of paleoclimates intrinsically rests on what one of its most eminent proponents, Martin Schwarzbach, once called the "paradoxical situation" of the exact sciences meeting the inexact:

> It is worth pointing out that the basic data have mainly been derived from geology (together with paleobotany in particular), i.e. from an "inexact" natural

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> science, while the often highly speculative attempts at explanation have come very largely from the "exact" sciences of astronomy, physics, geophysics, and meteorology (Schwarzbach 1963, 3).[1]

Notwithstanding the fact that geoscientific fields like meteorology were, at this time around the middle of the twentieth century, still struggling to be labeled an "exact science," Schwarzbach points to the crucial entanglement of observational data and physics-based models that together constitute the field of paleoclimatology.

With the advent of computer modeling within the earth sciences – just about the same time as when Schwarzbach wrote the lines above – the distinction was poised to become even more blurred. Descriptive, explanative, and speculative methods of scientific inquiry are now inseparable in daily practice. Paleoclimatology today draws its conclusions from the practical interdependency of data-based reconstruction and model-based simulation, or, as Paul Edwards has put it for climate science in general, models are always "data-laden" and data is always "model-laden" (Edwards 2010, 279). Mathematical modeling of geological formations indicates suitable sites for collecting proxy data, which provides the statistically assimilated data set to constrain numerical experiments reconstructing paleoclimatic episodes that in turn help to interpret the proxy data again. "The strength of using climate models with geological data lies in the iterative process, whereby one discipline can be used to test the other" (Williams et al. 2007, 2).

Just to make sure, this argument is far from denouncing paleoclimatology as having saddled on an infinite regress, merely constituting a ludicrous example of manipulative, or, to put it more positively, playful "postmodern" science, in which overvalued technology meets value-driven "postnormal" science.[2] In fact, in this paper I want to contest the idea of an epochal epistemic break, a revolutionary shift from science to "technoscience" (Nordmann, Radder and Schiemann 2011). This paper argues for an astounding continuity in paleoclimate research – devoid of any paradigm shifting so prevalent in the discussion on twentieth century science – and highlights the fundamental blurriness of exact and inexact methods, of descriptive, explanatory, and model-based approaches, as if paleoclimatology has never been (post-)modern.

In my opinion, the deep integration of models and data shows the very pragmatic and somewhat opportunistic tendency of paleoclimatology, or better:

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[1] The term "paradoxe Feststellung" appears in the German original (Schwarzbach 1950, 1).

[2] See, e.g., Sundberg (2010), who investigates the distinction between a "modern culture of calculation" and a "postmodern culture of simulation," arriving at the conclusion that both are mixed in current practice; Forman (2007), who accuses science and technology historians of having missed the (regretful) ideological shift away from the modern primacy of science over technology since the 1980s; and Krauss, Schäfer and von Storch (2012), who contend a messy mixture of scientific knowledge with normative judgment in the realm of climate science.

climate science in general, to disrespect – not in theory or rhetoric, but in practice – disciplinary and methodological boundaries. As such they are very symptomatic of the constructive practices by which the earth sciences cope with their intrinsic reliance on heuristic strategies, approximative solutions and merely adjusted hypotheses to eventually arrive at astoundingly robust results. Instead of reproaching the earth sciences, over and over again, with the social construction of scientific facticity, they might better be approached as being invested, often quite consciously so, in a hands-on effort to construct, or better, compose the world as such. In the end, they stand for a creative engagement with the real-world dilemma of arriving at meaningful interpretations in the mere empirical realm, that is, to put it more bluntly, the "noise" of the "real."

While the aim of the present paper is not to analyze the perceived epistemological tension between models and proxy data (and the apparent vaporization of that very tension in digital environments), it exemplifies my theoretical standpoint by highlighting a radical instance of this empirical realm: the reconstruction of deep-time events, devoid of any reliable data per se, as a means to determine geological analogues for the rapid climatic transition earth is currently facing. Stripped of anything like certainty the search for deep-time paleoclimatic analogues probes geoscientific evidence at its conceptual limits, yet presents a fruitful effort to gain insight into a worldly reality too overwhelming to neglect. The extremity of this scientific endeavor offers two characteristics of paleoclimatology addressing current social realities. By demonstrating possible consequences, they immediately evoke a call for societal responses to the disruptive transition of the earth system. And by linking the deep time to the present – essentially collapsing the notion of historical (human) time to geohistorical (earth) time – they provide the referential basis for a shifting narrative of the social itself.

Now, in this paper I am less concerned with the political or even philosophical dimensions of studying abrupt climate changes in deep time than with the epistemological preconditions of such undertakings, namely the inherent heuristical framing of the problem and the material practices that historically evolved in formulating this very framing. A historical analysis of the instruments used and the general procurement and processing of data might help to better understand the potency of paleoclimate science in the current discourse across the sciences and humanities on the manifold interlocking of humans and nature, so nicely summarized by the term "Anthropocene," the proposed new geohistorical epoch in which humankind has become the dominant biogeophysical force. In consideration of paleoclimatology's co-authorship in defining so-called "planetary boundaries" and its matured skills in dealing with and on the basis of uncertainties as a matter of principle, I see paleoclimatology as a prime example among the earth and climate sciences' long march to finally become not only more visible to a wider public and also more closely entangled with the social sciences but even role models for the sciences in general.

The earth and environmental sciences, a long time treated shabbily for being inexact and too descriptive, have successively advanced a method which is ubiquitous today, a method I would like to call "modeled semi-empiricism". The sheer technical feasibility, but also the undeniable success of the epistemic entanglement of (partly modeled) environmental field data and deterministic or statistical modeling over the course of the last 60 years or so, has catapulted climate science into the rank of a principal method for understanding processes in nature. At the same time it has shown, among the variety of its methods and cultural traditions, a general capacity to include social realms (see Oreskes 2015, in this HSR Special Issue), irrespective, for a start, of how "the social" is represented (or "parameterized") in such semi-empirical models. This has come about not only because of its holistic pretence to create a "global panopticon" of environmental monitoring and form a giant interactive earth system science (see Aronova 2015; Uhrqvist 2015, both in this HSR Special Issue) but decisively because of its self-reflexive handling of its own epistemic limitations within a large discursive forum such as the IPCC, with all its pitfalls and perils. The apparent success in detecting and predicting, carefully monitoring and analyzing, and also convincingly explaining the climate crisis has even made more avantgardistic parts of the humanities advocating a more constructive approach, renouncing their own critical folklore.[3] Even philosophy lends never-before-seen prestige to the earth sciences, whispering "[M]ore difficult, subtle and complete, the life and earth sciences, henceforth put in the center of cognition, take over. They practice a more sharing, open, connected way of knowing, in which he who knows participates in the things he knows" (Serres 2012, 33).

In its first part the paper introduces three interconnected conceptual terms that are central to the heuristic rationale of paleoclimatology: the earth as an experimental setting to study catastrophic events in earth's history that could serve as geological analogues for the current transition phase into the Anthropocene. To illustrate the epistemological foundations of these key terms, the paper then explores the history of the essential sector of deep-time proxy-data generation and analysis (while putting aside for now the use of such data in constraining computer simulations that "hindcast" such events):[4] the exploration of deep-sea marine sediments and their suitability for exhibiting past climatic change. In a very peculiar fashion, it is the allegedly calm ocean floor that today reveals the global nature of climate based on an endless variability, eventfulness, and transience, where climate never "is" but always "becomes." Moreover, it is the crucial function of certain microorganisms, so-called foraminifers, that serves as key proxy for the reconstruction of paleotemperatures

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[3] A prime example is Latour (2004), which, to some extent, resulted in Latour (2010).

[4] The usage of climate models or more precisely of so-called General Circulation Models (GCMs) for reconstructing paleoclimatic events is part of the ongoing research for my PhD thesis on the history of atmospheric modeling.

in deep time. Thus, this second part combines a historical description of the genesis of paleoceanography, i.e. the recovery and interpretation of stratigraphic discontinuities in biogenous deep-sea sediments, during the era of the great oceanographic expeditions in the hundred years or so between the mid-nineteenth and mid-twentieth century and with the start of isotopic analysis of such sediments in the aftermath of World War II. While the disciplinary backgrounds and technological settings of these two methods differ greatly – the one being "fieldwork" on a research vessel and the other bearing on the controlled arrangement of instruments usually called a "laboratory" – the heuristic goals of their respective endeavor remain commensurable, if not the same. No paradigm shift ahoy!

2. In Search of an Analogue for the Anthropocene

In May 2011, on the occasion of a workshop on the evidence and meaning of the Anthropocene, the president of the Geological Society of London, Bryan Lovell, remarked:

> The beauty of looking in the rock record is you don't have to run a computer model to see what's going to happen. You see the whole thing. When you put say 2,000 gigatons [billion tons] or thereby of carbon into the atmosphere rapidly a certain number of things happen. It gets hot. The oceans get acid. They run short of oxygen and as a result quite a number of animals become extinct. And in the rock record what you see subsequently is the extinction event is recorded, and you see the draw-down over a period of 100,000 or 200,000 years of the carbon from the atmosphere, which is manifested on the floor of the ocean as a development of a carbon-rich mudstone. It's just a very fine-grained rock. It's just a stinking black mud laid down on the floor of the ocean.
>
> The people who are saying to us, we're carrying out an experiment with earth and we don't really know the outcome, well that sounds dramatic but strictly speaking it's not true. Earth itself has run the experiment several times (Revkin 2011).

While the stratigraphic evidence for the Anthropocene is still under debate (Zalasiewicz et al. 2011), the term is already endorsed by many across the geo-, climate and ecological science communities and is even swiftly gaining momentum in many fields of the humanities as well as the arts.[5] Yet, Lovell's statement is focusing not so much on the agency of industrialized mankind as on the comparability of current trends in the earth system to former geohistoric episodes. In mirroring the human-shaped present in deep-time events, the study

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[5] See the two-year "Anthropocene Project" at the Haus der Kulturen der Welt, Berlin: <http://www.hkw.de/en/programm/projekte/2014/anthropozaen/anthropozaen_2013_2014.php> (Accessed March 14, 2014).

of paleoclimates effectively acclimatizes us to the possible scopes and scales, and thus the political or even civilizational burden of the Anthropocene.

More precisely, Lovell is even evoking a more technical term than comparability: reproducibility! Apparently, in the Anthropocene – the age that could also be described as the epoch of the technical cultivation of fossil energy by modern science and engineering – it sounds plausible to regard the earth as an experimental system in itself. Earth itself is providing an experimental setting for evaluating the near future and we would just have to look into the lab notebook of nature to grasp its outcome. Geology is seen not as a mere empirical science but as the provision of a script for the future.

A recent paper by Alan Haywood et al. (2011) reviewing possible candidates for past intervals in earth history that are comparable to current abrupt climatic change gives a more sober statement but still points in the same direction, while also reflecting on the social value of such paleoclimatic endeavor:

> Given the inherent uncertainties in predicting how climate and environments will respond to anthropogenic emissions of greenhouse gases, it would be beneficial to society if science could identify geological analogues to the human race's current grand climate experiment. This has been a focus of the geological and palaeoclimate communities over the last 30 years, with many scientific papers claiming that intervals in Earth history can be used as an analogue for future climate change (Haywood et al. 2011, 933).

Indeed, the geological archive is providing reasonable ground for researching the causes and consequences of disruptive global warming. If one could identify a true geological analogue to the present, the one signal among the noise of deep time that matches the current mark humankind is poised to leave on earth, one could almost gain a template to the "human race's current grand climate experiment." This would provide an invaluable asset not only for concretely defining the "planetary boundaries" under which humanity finds its Holocene-type "safe operating space" but also for laying the groundwork of a "planetary stewardship" (Rockström et al. 2009; Steffen et al. 2011). By entrusting geology – and in particular marine sedimentary geology – and their tools of geochemical analysis to uncover firm knowledge stored, and hence, within that rationale, also initially "produced" by, the earth's crust, one would be able to install a reliable geoscientific early warning system for boundaries being transgressed. This database of deep-time earth history would then allow a palpable framework to be built for socioeconomic instructions on what is to be avoided in the shallow future. A sound basis for developing planetary policy, governance, and management in the Anthropocene might finally be around the corner (cf. Dörries 2015, in this HSR Special Issue).

Moreover, the statements by Haywood et al. (2011) and Lovell (2010) underline the highly welcome availability of an alternative to numerical prediction models. In suggesting a total comprehensibility of the geological record, Lovell even goes so far as to deny the necessity of computer models at all.

What is the need for highly specialized models when you can actually "see the whole thing?" In this rationale based on geological evidence, proxy data becomes a silver bullet to finally silence climate denialists: the accusation of reductionism and of building a cascading architecture of uncertainty that is so tediously raised by climate skeptics against the use of "*in silico*" methods would be invalid and a secure "*in vivo*" knowledge about Gaia's behavior would be granted. Being one to one identical with earth itself, the paleoclimatic experiment is complete in its experimental arrangement and thus provides clear answers within its vast yet readable archive.

This argument, of course, is as much enticing as it is misleading. How so? Before answering this question let me briefly give you an example of an event that has the theoretical potential to serve as geological analogue for current global warming. One particular case that comes reasonably close to the current climate disruption is the Paleocene-Eocene Thermal Maximum (PETM), dated at 54.8 million years ago (Haywood et al. 2011, 939-41). Paleontologically, it is characterized by a large extinction of benthic species (organisms living close or at the bottom of the oceans) and a mammal turnover on land. In fact, it was Charles Lyell who already christened this dramatic transition Eocene, "as indicating the dawn [eos] of the present state of the animate creation" (Lyell 1833, 225, see also 55). However, the PETM itself entered the scene some 160 years after Lyell's seminal work with the availability of extremely long marine cores and high-resolution dating methods (Kennett and Stott 1991). Today, the PETM constitutes a prime example of what is now called a "hyperthermal event," stressing the fact that it presents an excessive but transient warming period on top of an already warm greenhouse baseline climate. And indeed, just like Lovell (2010) asserted, this event, which is "recorded" in different marine sediments across the globe, is visible to the naked eye: "The PETM is represented by 25 cm thick, dark, calcareous ooze embedded within a uniform sequence of white calcareous nannofossil ooze" (Zachos et al. 2003, 1552).[6]

However, without sophisticated drilling equipment to penetrate the deep-sea floor the "deep-time horizon" would remain entirely unfathomed. Moreover, without high-tech instrumentation the underlying cause of the high-contrast discontinuity, that is so nicely visible in the core segment, would remain entirely elusive. It needs a whole assemblage of material configurations – drilling vessels, hole re-entry cones, core repositories, and above all a highly sensitive mass spectrometer consisting of ionizer chambers, lenses, apertures, circuits, processors, but also reference material, chemical reagents etc. – to mediate between what the field oceanographer "sees" and what the laboratory paleoclimatologist "understands" (while both are, of course, often times one and the same person). There simply is no geohistoric "event stratigraphy" without

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[6] For a visual impression see e.g. <http://www-odp.tamu.edu/publications/198_IR/front.htm> (Accessed March 14, 2014).

walking through this highly sophisticated process of paleoceanography: recovering deep-sea sediment cores on large-scale, internationally financed expeditions, organizing their archival storage and registry, and analyzing them according to the highly sophisticated and calibrated methods of stable isotope geochemistry.

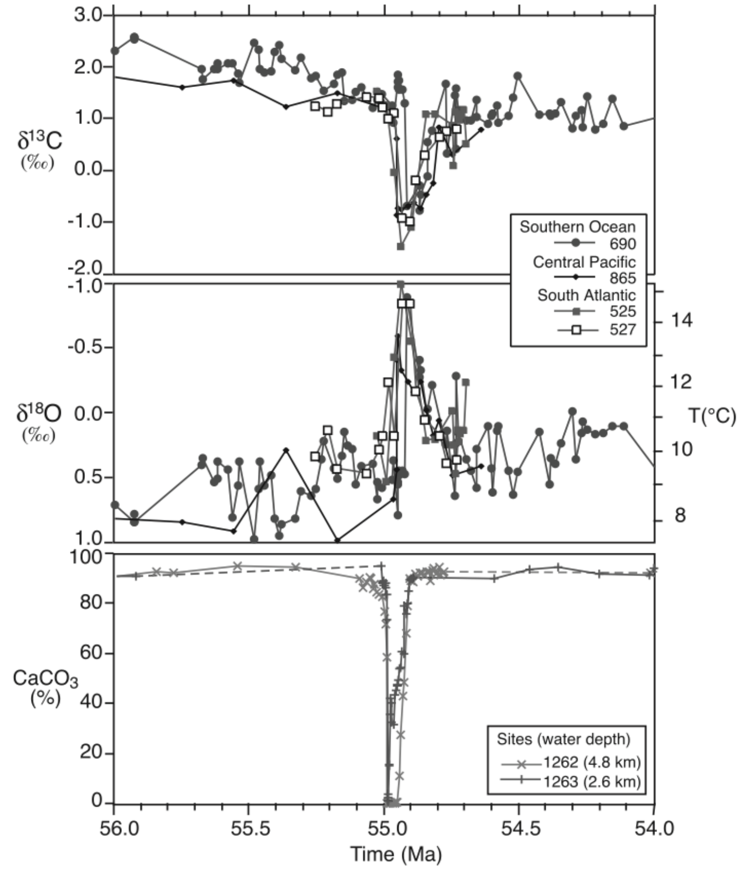
Finally, the isotopic signatures extracted from the few shells of calcifying organisms that survived the mass extinction – for the Cenozoic usually foraminifera or short: "forams" serve as index fossils – reveal a threefold signal (see Fig. 1): a large impulse of light carbon ($\delta^{13}C$), suggesting a massive release of methane into the ocean, which nicely correlates with a significant acidification of the ocean and a pronounced warming of both ocean and atmosphere as indicated by the paleotemperature proxy ($\delta^{18}O$).

When applied to a geological timescale, these "excursions" of the plotted isotopic curves appear very abrupt. Probably set off by two impulses each less than 1,000 years in duration and developing to full scale for a few ten thousands of years, before recovering to previous levels after some 170,000 years in total (Röhl et al. 2007). Note that all these numbers are not coming as a package insert with the geological record but have to be calculated according to, e.g., cyclostratigraphic age models. Now, for finding true correlations and, hence, causal relations one would need a much higher time resolution. In the end, what exactly is a synchronized "event" when speaking about several thousands of years? Yet, a more precise dating is almost impossible in such deep-time realms, due to the mixing of sediments by bottom-dwelling species ("bioturbation"), local distortion of the record by tectonic events (earthquakes, slope failures, "turbidity currents") and many reasons more. Even if reconstruction efforts allowed for a higher resolution it would still be far off the timescale of current political planning horizons. Hence, it is, in a perplexing way, at the same time very comprehensible and very incomprehensible when Bryan Lovell refers to the lesson we should learn from the PETM: "Changes in climate that took place long ago can now reasonably be compared with those seen in the recent past. [...] We are in danger of repeating that 55 million-year-old global warming event, which disrupted Earth for over 100,000 years" (Lovell 2010, xi).

Yet, besides the problem with the temporal resolution of the geological archive, the characteristic attribute of the modern scientific experiment, namely to be reproducible, is off the table too. In their study – which, by the way, relied entirely on simulation runs of coupled atmosphere-ocean models constrained by given proxy data – Haywood et al. (2011, 949) concluded that "Earth history fails to provide a true and direct analogue." All promising candidates for deep-time analogues, including the PETM, "either represent equilibrium climate states to a long-term CO2 forcing – whereas anthropogenic emissions of greenhouse gases provide a progressive (transient) forcing on climate – or the sensitivity of the climate system itself to CO2 was different" (Haywood et al. 2011, 933). As a matter of principle, earth history does not repeat itself!

Although, one certainly could see a pattern here that comes close to Marx's famous dictum on the repetition of history: What first was an evolutionary tragedy of mass extinction seems to become a blatant farce of denialism today.

Figure 1: The "Signals" of the PETM



Source: IPCC AR4 WG 1, 443.

In any case, the models themselves are not to blame for that outcome. On the contrary, they provide a robust heuristic for how and why earth history does not repeat itself.[7] The very epistemological essence and model-oriented practice of

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[7] The science-cultural adequacy of GCMs to appropriately address the current system transition is the central argument of my PhD thesis, still in progress. I show how the encoded heuristics are founded on a long descent of technical apprehensions of flow and that per-

what today is called “earth system science” is the nonlinear behavior of complex systems in which the precise evolution of a certain climatic state or the transition between several states is always unique and singular. Natural recurrence is, speaking in the specific terminology of numerical replication, undermined by different initial conditions and the chaotic behavior of the general system. Introducing his concept of transitive and intransitive climatic states Edward Lorenz already pointed out in 1964: “the atmosphere is essentially a one-shot experiment, and we cannot introduce new initial conditions and perform the experiment again” (Lorenz 1964, 2). In the case of the PETM, for instance, such incomparableness by principle is based on a “different continental configuration [during the Paleocene-Eocene], absence of continental ice and a different base climate, which limits the PETM’s suitability as the perfect future analogue” (Zeebe, Zachos and Dickens 2009, 579).

It is important to note here, that the negative conclusion of Haywood et al. (2011) is not a new insight but just another confirmation of an old suspicion. Already in 1990 paleoclimologist Thomas J. Crowley criticized the “continued use of the term analog”:

> [A]lthough paleoclimate studies can contribute much valuable insight into mechanisms of climate change, continued efforts to identify past, warm periods as analogs rest upon often unstated assumptions that are probably not valid. The future greenhouse warming may, therefore, represent a unique climate realization in earth history (Crowley 1990, 1282).

The uniqueness of future or even current climate is another point that questions the suitability of the analogy method, attacking comparability not from the deep-time but the present end. The Holocene climate is highly exceptional in Earth history. It is a very unusual interglacial period, characterized by relative sea-level stability while much of the geochemical system is not in a steady state due to anthropogenic perturbation (Hay, DeConto and Wold 1997).[8] In the end, when eminent paleoceanographers like William W. Hay and Robert M. DeConto turn the uniformitarian principle upside down and ask “Is the past the key to the future?” their answer is: “Not really, but ...”!

> The past climates of the earth cannot be used as a direct guide to what may occur in the future. To understand what may happen in the future we must learn about the first principles of physics and chemistry related to the earth’s system. (Hay, DeConto and Wold 1997, 471-2).

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ceived “scientific revolutions” are mere technological shifts in a general epistemic framework that is based on a long tradition of comprehending earth as a fluid-dynamical system.

[8] This paper is very interesting in the sense that it attributes many characteristics of what we today regard as features of the Anthropocene still to the Holocene. The famous paper of Paul Crutzen and Eugene Stoermer that popularized the term “Anthropocene” came out only about three years later (Crutzen and Stoermer 2000).

In line with academic sportsmanship, the general strategy of the paleoclimatic community is to turn the negative result into a positive task, as confirmed by IPCC's Fourth Assessment Report of 2007:

> The Working Group I (WGI) WGI FAR noted that past climates could provide analogues. Fifteen years of research since that assessment has identified a range of variations and instabilities in the climate system ... These past climates do not appear to be analogues of the immediate future, yet they do reveal a wide range of climate processes that need to be understood when projecting 21st-century climate change (Le Treut et al. 2007, 107).

The data gathered and the models created in the never-to-be-accomplished attempt to compile deep-time analogues are seen as an essential asset in enhancing a synoptic understanding of the many interactive processes involved in climate change. Moreover, in acknowledging the impossibility of one climate episode serving as the blueprint for another, the earth system community is now eager to describe the Anthropocene as a "no-analogue" state within earth history, stressing both the essentially unique outcome of the human intervention and the previously unseen rapidity of the systemic transition which this intervention apparently entails (Steffen et al. 2004, 264).

It is important to note that even under the condition of a system's theory framework, it is the earth perceived as an experimental arrangement that serves the goal. As

> many are becoming aware that one cannot understand the present, let alone forecast the future, simply by looking for causality in the past through analogues and then extrapolating toward the future ... each [paleoclimatic] case study serves as if it were a past experiment that, if followed over at least some part of its trajectory, provides knowledge about interactions between different components of such systems under different conditions (Van der Leeuw et al. 2011, 3).

Curiously enough, this is written by the authors of the monumental IHOPE project, which sets out for a holistic approach in "building integrated models of past human societies and their interactions with their environments" (Van der Leeuw et al. 2011, 1). While this grand project might be a "frustrating experience," as one of its authors has recently remarked, the theoretical revisit of historical time is certainly of much interest to a historian trying to get to terms with the valence of the concept of the (non-)analogue.

Of course, the experiment metaphor used by Lovell (2010) and Haywood et al. (2011) has long become an almost idiomatic expression. In fact, it reconnects to a long tradition in the earth sciences, at least dating back to nineteenth century geology and seismic research.[9] Roger Revelle and Hans E. Suess famously used it in 1957 in what has become one of the most cited sentences in

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[9] See, e.g., Westermann (2011, 72): "By the end of the nineteenth century ... earthquakes were seen as experiments in the scale of 1:1, with the globe being the object under study."

the history of climate science: “Human beings are now carrying out a large geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future” (Revelle and Suess 1957, 19). Interestingly enough, they already singled out the possibility of a conclusion by analogy. Ed Lorenz did the same – just a few years and some computer usage later – as his quotation above indicates.

The same longstanding tradition applies, of course, to the term “geological analogue.” One does not need to venture into a monumental history of the idea of analogism, of grasping the unknown by the known, to recognize the term at the heart of modern geology. “To reason by analogy” is the very essence of Lyellian uniformitarianism, leading to the methodological principle of *the present being key to the past* (Fairbridge 2009, 417). Although devalued to some extent today – as we have seen in the case of the exceptional Holocene providing no suitable baseline climate for the rest of earth history – it seems as if “to reason by analogy” is itself a timeless formulation of the scientific desire to model on the comprehensive evidence of history. No matter whether in the 1990’s figures like Thomas Crowley or William Hay already responded negatively, the rhetorical question of whether the uniformitarian principle can “be reversed and extended so that the past *becomes the key to the future*” still lingers in 2011 (Haywood et al. 2011, 934), once again evoking the old quest for the Holy Grail of the Anthropocene.

All along these decades of research-quest(ion)-recycling, a decisive bulk of the rationale connected to the term analogy has quietly moved from the physical geological analogue towards a “numerical analogue,” that is, a paleoclimate generated and interpreted as a numerical experiment using Earth Models of Intermediate Complexity (EMICs) or General Circulation Models (GCMs) (Vaughan 2007, 21). Owed to the new strategy of understanding system’s behavior rather than finding 1:1 matches, the tendency now is to create a neatly fitting simulation of the geohistorical episode. Instead of searching for a deep-time analogue of the present in the empirical strata one now composes a virtual analogue of the “catalog of what has happened” in order to learn about Gaia’s behavior under extreme conditions – conditions we might face in the near future.

> The record of past climate conditions provides us with a catalog of what has happened. It shows us what is possible but offers only indirect clues about the factors controlling climate. The goal of paleoclimatology and paleoceanography is to determine the relative importance of factors producing specific climate conditions and climate change. By understanding the mechanisms that have been important in the past, we gain insight into what may happen in the future. The fundamental mechanisms of the climate system are best explored in simulations of the earth’s ancient extreme climates (Hay, DeConto and Wold 1997, 488).

Notwithstanding the complexity of holding too many keys for the future in the hand for too many locks, it is the sheer evidence in the strata laid out before our eyes, that might finally activate much needed mitigation efforts. The powerful rhetoric of paleoclimatic evidence and geological analogues becomes embedded in a utilitarian message, turning paleoclimatic data into an essential asset in almost cognitively overcoming the current sociopolitical gridlock. Analogies here are not meant in a direct, one to one sense. A general resemblance is all that counts in the semi-empirical modeling realm that helps to identify and quantify individual processes within the total sum that is earth.

However, in order to write a historical epistemology of the geological analogue of any two events in geohistory, one first needs to explain what kind of temporality is carried, mobilized, inflicted by this very term, the (catastrophic) “event”. What does this term mean on a geological timescale, where abruptness is, in the end, always a function of (perturbed) spatial resolution? But also: where does the notion of “climate” belong in the epistemic tension between lawful repetitiveness and unlawful historicity? While nineteenth-century geology developed a genuine interest in sometimes drastic but regular changes, that is, mostly the occurrence of ice ages, how did the idea of abrupt, contingent, and asymmetrical change come into play? And, above all, how did contemporary climatology, which basically understood climate as a geographic mosaic, which is to be described (Heymann 2009, 175), align itself with such geological questions in order to arrive at a historicity of the climate itself?

Of course, such questions are extremely broad and the following, historical part of this paper cannot, in any meaningful way, give sufficient answers to them. Instead, it narrows down the vastness of the subject by focusing on the case of marine sediment sampling in the period of ca. 1850 to 1950, when the notion of climate changed from a stable homeostatic or cyclical temporality of quasi-permanence to a chatoyant geohistory that is, more often than not, characterized by an irregular, event-like nature. While the history of studying and debating (cyclical) climatic changes is already a key theme in the historiography of (terrestrial-based) geological paleoclimatology – ranging from the “desiccation theory” trying to explain elevated shorelines to the glacial theory based on “erratics” (dislocated boulders)[10] – the history of paleoclimatology based on marine proxy data, that is, paleoceanography, seems fairly undeveloped. Yet, the relatively unperturbed environment of pelagic (far from the coast) sediments has proven to be decisive in gradually entering the deep-time horizons that are critical in finding potential analogues like the PETM.

Thus, by focusing on two historical aspects of empirical data collection and analysis – the sampling of the oceanic bed by the first oceanographic deep-sea expeditions and the paleoceanographic analysis of found climate proxies by early laboratory methods – I want to present a long-time perspective on how paleoclimatology embarked on the “focus of the geological and palaeoclimate communities over the last 30 years” or so on finding a geological analogue for

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[10] For a general overview see Fairbridge (2009); for an in-depth description see Rudwick (2005, 2008); and for the long-established folklore of the discipline itself, Schwarzbach (1963).

the current climate crisis. While the two episodes do not comprise or directly precede the particular time period of the last 30 years, I want to highlight the more general epistemological foundations of their contemporary endeavor by looking further back into the formative period of paleoceanography as a modern discipline.[11] In juxtaposing two highly different forms of field practices I argue for an astounding persistence if not *longue durée* of the historicization of climate, i.e. climate change, and the epistemic valence of field data within that process. In this, I concur with Sverker Sörlin, who wrote:

> [T]here are longue durées of disciplinary ideas, and I would like to suggest that these ideas are particularly strong when they are bound to field experiences, that is when the knowledge is of what we may call a bodily nature and has involved investment in physical work, installations and instrumentation of a fixed and long-term character. The field scientist has somehow physically appropriated the reality that he is at the same time claiming (Sörlin 2009, 107).

There is a powerful continuity when it comes to central themes within the earth sciences, themes that just reappear in a different technical guise, transformed by their material rearrangement and their vocabulary but not by their heuristic grasp of the world that is always to be recomposed: revolutions in the original sense of recurrence. Due to the format the following historical part I cannot present a long row of cases supporting the validity of this general hypothesis. Thus, it concentrates – rather than on key figures in the geological, paleontological, and geographical debates of climate variability like by T. C. Chamberlin, Louis Agassiz, or Eduard Brückner – on oceanographers like Emil Philippi and nuclear chemists like Harold Urey. However, in fact, the true “heroes” of the story are cannonballs, foraminifers, piston corers, and mass spectrometers.

3. “Geschichtung”: A Brief History of Paleoceanography

As James Delbourgo (2011, 154) writes in his study on “collecting the world under water”, the ocean floor was “divine in its unknowability” for early modern natural philosophers. While corals, shells, and Spanish silver coins, all of shallow-water origin, gave way to the picture of “an intensely fetishized zone of collection and signification” (ibid., 151), the deep sea itself remained an arcane place. Even “by the late eighteenth century, Europeans understood the deep sea as a great void that was empty and featureless, the antithesis of civilization” (Rozwadowski 2008, 5).

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[11] A quick search on Google’s Ingram viewer reveals that the term „paleoceanography“ itself goes back at least until the end of the nineteenth century, while becoming actually utilized only after World War II. After a first peak in the 1950s, usage really took off during the 1970s, and is nowadays coming down again, <https://books.google.com/ngrams/graph? content=paleoceanography> (Accessed March 14, 2014).

The pelagic deep sea was also an unfathomable scene. Sounding the bottom of near coastal waters for navigational purposes and examining the type and color of the ooze, silt, or sand that stuck to the plumbing line was common seafaring practice since at least the time of Herodotus (Krümmel 1902, 83). Yet, a regular sounding line was quite useless in the open sea, where heavy currents and the enormous depths defeated attempts to measure, let alone to recover. So in order to "extort an answer from the silent ocean" and "reveal the secret of its depth" (Hartwig 1859, 8),[12] some other techniques were needed. With the advent of transatlantic telegraphy in the mid-nineteenth century the silent ocean bottom finally became noisy, revealing some first information about its composition. Sponsored by American and British navies, the first controlled effort to sample deep-sea sediments was undertaken to examine the sea floor for its suitability to safely store telegraphic cables.[13] On a request by Samuel Morse, Matthew Maury, "data guy" (Edwards 2010, 34) and editor of the monumental *Physical Geography of the Sea*, personally responded:

> Berryman brought up with Brooke's deep-sea sounding apparatus specimens of the bottom from this plateau. I sent them to Prof. Bailey, of West Point, for examination under his microscope. This he kindly gave them, and was quite as much surprised to find, as I was to learn, that all those specimens of deep-sea soundings are filled with microscopic shells – "not a particle of sand or gravel exists in them." These little shells, therefore, suggest the fact that there are no currents at the bottom of the sea whence they came; that Brooke's lead found them where they were deposited in their burial place after having lived and died on the surface, and by gradually sinking were lodged on the bottom.[14]

By recovering these "trophies" (ibid., 210) from the ocean floor, Maury holds a first indicator of the existence, or non-existence, of movements in the deep sea. While obtaining (sandy) bottom sediments has been regular practice in the bathymetric coast surveys since the 1840s (Rozwadowski 2008, 84), no equipment has been devised to explore depths in mid-Atlantic. Now, Brooke's "deep-sea sounding apparatus" came in very handy. It essentially consisted of a metal pipe inserted into a heavy cannonball. At hitting the bottom the cannonball released the pipe, which continued to further penetrate the first few inches

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[12] Translation by Christoph Rosol, with thanks to Christina Wessely for the hint to this quote.

[13] Individual attempts were made earlier, first and most notably by the British polar explorer Sir John Ross in 1818, recovering sediments with the aid of a deep-sea gripper from a depth of 1970 m in Baffin Bay (Krümmel1902, 39). However, these early attempts were not undertaken in open-ocean zones and present rare exceptions anyways, far from furnishing any reliable empirical data on the constitution of the sea floor.

[14] Letter of Maury to Morse, 23/02/1854, printed in Murray & Peake (1904, 4-5), emphasis in the original. Cf. the almost identical formulations in Maury (1855, 209-10).

of ooze. Wounded up, the sediment in the pipe was proof enough for the crew that the sounding had indeed been successful (Maury 1855, 206).[15]

Maury's inference drawn from the seemingly unperturbed ooze is already bringing time into play here: a continuous and steady "sinking and lodging" of organisms over the ages. In 1904, famed Scottish oceanographer and marine biologist John Murray, together with the civil engineer Robert Edward Peake, calculated the sinking rate of the micro fauna by the elevation of ooze resp. detritus above the transatlantic cables that had been laid some 50 years earlier (Murray and Peake 1904).[16] This effort is crucial, not because it underlines the continuing nexus between telegraphy and oceanography, commercial engineering and the deposition of organic material, but because it highlights a turning point in the interest in the oceanic bottom floor. Murray and Peake's aim here was not to merely present its current state, i.e. to map it. Instead of sounding and creating a cartographic representation, the aim was to use it as a proxy for calculating a rate, a variable as a function of time, a physical process. And these quantified flux rates brought something else to the fore: variability!

The organisms, "after having lived and died on the surface," are sinking to the floor, bury the cable. Yet, they amass differently in different regions. Already in the aftermath of the famous British Challenger expedition (1873-1876) Murray alluded to the different distribution of certain kinds of microorganisms (he was already referring to foraminifers), interpreting it in accord with contemporary rationale, that is, in terms of zonal or geographical climate (Murray 1897, 23). In this view, the regional differences of cold and warm ocean currents determine the variety of a certain species, hence, the state of a biological entity, and its spatial distribution across the globe (chorology) reflects on its individual environment. This zoological or botanical classification of a climatic region is, of course, one of the central tools of classical climatology, being both a descriptive and a systematizing science, but neither a predictive nor retrodictive one (Heymann 2009, 175).

However, where there is space and geography there is also time and geology. For many expeditions, even after the Challenger journey, oceanographers were just able to extract unstratified ("ungeschichtete") sediment samples and therefore kept on believing in a more or less constant deposition of recent organic material. It was not until the Gauß expedition made its way into the Southern Ocean (1901-1903) that this view changed. Particular equipment used by the Gauß crew, so-called "Bachmann'sche Schlammröhren" ("Bachmannian

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[15] The carrier cannonballs themselves remained on the sea floor, thus possibly bewildering future oceanographers and/or historians who will scan the sea floor again over the strange pattern of what appears to have been a perplexingly linear naval battle.

[16] Their result suggested an accumulation of some 2.5 cm within 10 years, overestimating the actual rate by far, probably due to the lack of awareness of how much the submarine cable itself had sunk in the meantime (Schott 1938, 322).

ooze pipes" or "corers"), allowed for an extraction of hitherto never seen cores of some 80 cm length and finally showed a distinct layering. From now on, sediment cores showing no discontinuities, no "history," became the rare exception (Philippi 1909, 2; Philippi 1910, 591). The Jena-based geologist Emil Philippi wrote:

> Krümmel [Handbuch der Ozeanographie, 1907] assumed for the few cases known to him, in which Globigerina ooze[17] was underlaid by red clay, a recent upward motion of the sea floor. [...] Yet, the general distribution of normal calcareous layers suggests a climatic cause. [...] The lower, less calcareous part of the subantarctic samples has probably been accumulated in a colder period, perhaps in a phase within the Quaternary ice age (Philippi 1909, 3-4, translation by Christoph Rosol).

Later, in the early 1950s, the Swiss geologist Eugen Wegmann described this turn to a climatic explanation of sedimentary stratification ("Geschichtung") as follows:

> In the third stage [of polar research] the dynamic picture of space is integrated into a historical perspective. Each of the phenomena of the polar regions gets a history, a beginning, a growth and an end, depending on the time frame. In this third stage, earlier methods are now accompanied by those methods that allow the traces of past events to be interpreted and defined chronologically.[...] Since Philippi realized that the samples of the German Antarctic expedition conveying two different types of sediment groups are witnesses of different climatic conditions ... a new archive has been made available: that of the sea floor (Wegmann 1951, 31-2, translation by Christoph Rosol).

Wegmann's words make it clear that the biostratigraphic method, that is, excavating ooze showing strata of colored clay alternating with strata of foram shells and analyzing these samples in another place and context, the laboratory, under the interpretative assumption of having a decent indicator of paleoclimatic fluctuations at hand, has been well established for quite a time already. In theory, climate change is a subject long explored; in practice, it was just lacking sufficient equipment.

Take, for instance, the German Meteor Expedition of 1925-1927 over the equatorial Atlantic. The great achievement of this expedition was the final mapping of the Atlantic seabed, the "conversion of the hidden 'nature' of the deep ocean into stable and communicable profiles" (Höhler 2002, 235). Yet, the coring efforts remained unsuccessful, often hauling up damaged cores that made a firm analysis of climatic layers impossible. It was not before the 1940s when the Swede Börge Kullenberg developed his "piston corer" that the recovery of non-distorted sediment cores was finally practicable (Pettersson 1948). This device, whose principle is still being used today, uses a remote trigger to release the weight, allowing a deep penetration of the ocean floor. With the

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[17] Globigerina is a genus of planktonic Foraminifera.

help of the piston corer the Swedish Albatross Expedition (1947-1948) was able to capture sediments of up to 9m in length.

A few years later, the German marine biologist Wolfgang Schott painstakingly analyzed three of the Albatross cores (Schott 1952).[18] By identifying foram species, determining their quantity and transferring that number onto an ordinary warm-cold axis, he obtained fluctuating curves that just needed to be geochronologically synchronized in order to show the alternation of the last glacial-interglacial cycles up to the Illinoian stage (ca. 300,000-130,000 years ago) (see Fig. 2). Neatly correlated curves fluctuating between warm (w) and cold (k) are now derived from single-celled microorganisms, which thereby have been duly incorporated into the long-established circus of paleontological "climate witnesses" ("Klimazeugen"), that is, proxies.

The tedious procedure that produced such quantities is described in Schott's earlier account of methods and instrumentation aboard the Meteor. First, the relative percentage of different foram species contained in a filtered and heat-dried sample was determined by counting the shells under a microscope – between 400 and 600 in each sample (Schott 1935, 45). In a second step, the processed sample was weighed to arrive at approximate numbers of total species in one gram of original sample material. To calibrate this procedure, 4,000 microscopic shells were actually counted, patiently so, producing a total weight of just 0.17152 grams as reference standard (Schott 1935, 112). There probably is no empirical science of contained-in-the-miniscule climate data without former advances in precision instrumentation and a scientific culture of pedantry.

Linear time series, variability, frequency: a true paleoceanography crystallized around the quantified analysis of certain microorganisms. "Paleoceanography deals with the history of the ocean" (Wefer et al. 1999, 2). It is the history of the fluid medium itself that is stored in the remnants of tiny shells. The medium continues to be the message: "In the composition of the community of the dead [Totengemeinschaft] the living community of pelagic foraminifers is still visible," Schott wrote in another paper, while "among the physico-chemical factors of the environment the temperature of the seawater is probably the most crucial" (Schott 1954, 192-3). Apparently, the transfer function of single-celled "Klimazeugen" is to reconstruct the ancient state of the sea in the silence of its depth. This general approach to earth's history does not decisively change if one replaces a microscope with a mass spectrometer.

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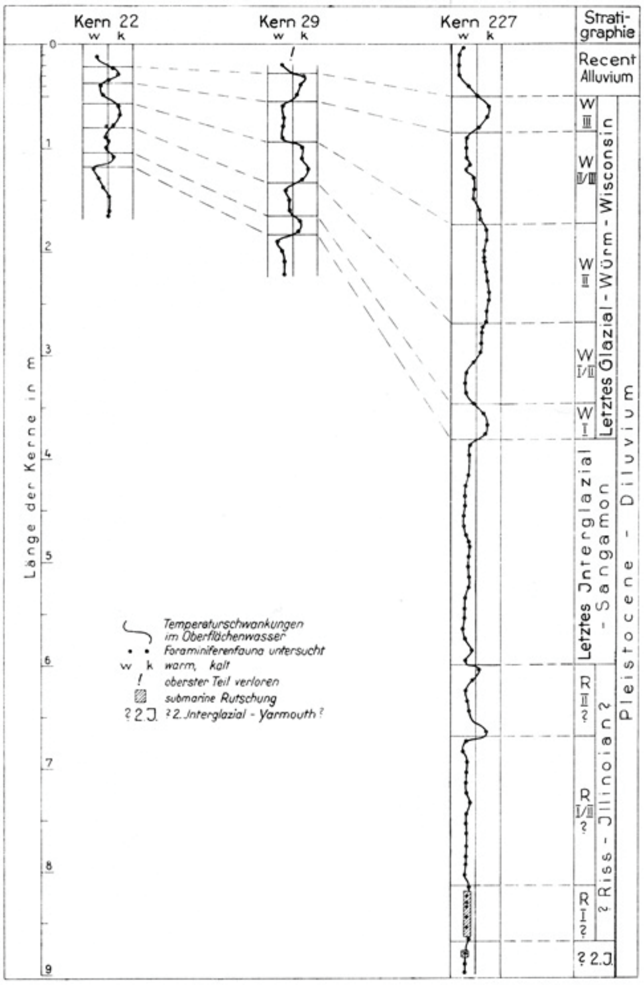
[18] On a more international level, the report of one of the participants of the exhibition, Gustaf Arrhenius, grandson of Svante, might be better known (Arrhenius 1952).

Figure 2: Schott's Paleotemperature Plot Derived from Foram Quantities



Source: Schott (1952, 26); Stratigraphische Gliederung der bearbeiteten 'Albatroß'-Kerne 22, 29 und 227.

As is very clear from the PETM example given above, today's data set of Quaternian as well as Pre-Quaternian climates is not based on counting individual foram shells but on the measurement of (stable) isotope ratios. At the very time Schott gave his paleoceanographic analysis, isotope geochemistry had already been established for a few years, adding a most potent while also spectacularly non-habitual treatment to the already wide set of empirical techniques that constitute the study of paleoclimates.

Geochemistry, the study of the concentrations, distributions, and general cycling of elements on earth, is essentially an old subject, bearing on its intimate relationship with agricultural and soil chemistry, but also with mineralogy and geology in a more direct sense. In fact, a variety of chemical experimental methods contributed decisively to the elaboration of geological theories in the seventeenth and eighteenth centuries, while also playing a decisive role in the neptunist-plutonist controversy in the nineteenth century (Fritscher 1991). Basel electrochemist Friedrich Schönbein, who coined the term "geochemistry" in the 1830s, had already spoken of the potency of the chemist "to write the history of the globe" by comparing distinct chemical formations, while Karl Gustaf Bischof, author of the first textbook on geochemistry in the 1840s, regarded the earth as a "vast chemical laboratory" (Oldroyd 2009, 410-1). The discussion about the notion of "experiment" in geohistory is closely tied to geochemical traditions.

Nevertheless, a discussion about the comparison of the distribution of different isotopes of one and the same element and their migration through the atmosphere, the ocean and earth's crust owes its entire possibility to the laboratory demonstration of such nuclear varieties among naturally occurring radioactive elements since around 1910 by radiochemists. Chemical elements possessing the same chemical and physical properties but differing in the atomic weights and radioactive properties (if radioactive) presented a burgeoning field of investigation and analytical techniques to study natural processes. As I am approaching the text limit of this paper, I can only mention a few, more or less stereotypical steps within a general history of isotope chemistry before I finally discuss its application to paleoceanography.

Given their name by Frederick Soddy in 1911, isotopes soon presented their suitability for a variety of methods. In the early twenties, George de Hevesy used radioactive isotopes to trace chemicals in plants and animals, thus already utilizing the circulation of isotopic species as an analytical tool for the study of living processes. Not much less important was the establishment of the radiometric dating method. By measuring radioactive decay of radioactive isotopes with a known half-life, the absolute age of rock formations could be derived. The first measurements of the decay of uranium to lead that resulted in this method had already been pioneered, *ante litteram*, in 1907, and geochronological dating became highly fashionable in the following decades (see e.g. Hahn 1932). High-precision measurements of the isotopic ratio between Uranium-235 (^{235}U) and Uranium-238 (^{238}U), most notably by Alfred O. Nier in the mid-1930s, then finally opened up the way to putting geochronology on a firm quantitative basis.

The accuracy of Nier's measurements was achieved by his own design of a much-improved mass spectrometer. In 1913, J. J. Thompson showed that ionized neon (that is, neon skimmed of electrons) passing through a magnetic and electrical field produces two distinct paths on a photographic plate according to two different atomic masses, i.e. isotopic weights (^{20}N and ^{22}N). Since neon is a stable element, this was the first evidence of non-radioactive isotopes. The first reliable mass spectrographs based on the photographic principle were constructed in the late 1910s by Arthur Jeffrey Dempster and Thompson's disciple Francis William Aston, the former presenting the basic design for all later developments. Besides the fact that Nier's late 1930s design obtained accurate mass spectra with relatively cheap material, thus allowing routine measurements, the specific importance was its application to lighter elements, most notably carbon (Nier 1940). He could show how the isotopic abundance of ^{13}C varies between different samples, though the origin of this natural separation process was unknown.

The final explanation for this process and its application to paleotemperature profiling was given by nuclear chemist Harold C. Urey in the late 1940s. In 1931, Urey had shown how to separate, or "fractionate," heavy and light hydrogen by a simple thermodynamic process, that is, distillation through careful warming: ^{1}H evaporates more easily than ^{2}H leaving a condensate of heavy hydrogen, or "deuterium." During the war, Urey worked on a combination of different separation processes – centrifugal separation, gaseous, and thermal diffusion – for uranium enrichment. The architecture of these apparatuses was essentially quite simple, given that it merely had to perform a cascading iteration of a physical separation process. However, many technical problems emerged, one of them resting in proper sealing (Hewlett and Anderson 1962, 124-8).

Setting up tent at the newly found Institute for Nuclear Studies at the University of Chicago in 1945/46, Urey then transferred his principle of fractionation theoretically to a variety of natural processes and chemical cycles. If ^{235}U and ^{238}U are separated by a thermal diffusion process within the laboratory the same could also occur naturally with lighter elements, which are abundant in the geochemical composition of the earth. On the other hand, this also means that one could deduce the given temperature by studying the isotopic composition. It soon became clear that, theoretically, a precise measurement of the ratio between different oxygen isotopes could provide a sort of "paleothermometer": "Accurate determinations of the ^{18}O content of carbonate rocks could be used to determine the temperature at which they were formed."[19]

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[19] Urey (1947, 578): the notion of "thermometer" appears on p. 579. As with the deuterium case, light oxygen (^{16}O) evaporates more easily than heavier oxygen (^{18}O), and is therefore more present in atmospheric CO_2 than in seawater. Conversely, ^{18}O accumulates in marine limestone, while this kind of "thermodynamic fractioning" is, as Urey noted, dependent on temperature: at higher ambient temperatures and, correspondingly, faster-moving molecules, fewer ions with ^{18}O atoms mineralize than in lower temperatures. This means that the housing shells or skeletons of marine organisms that have been built in warm periods have a lower ^{18}O value. Comparison of the isotopic composition of calcium carbonate samples with the standard ocean water would then yield a "palaeothermometer."

In a 1948 lecture titled *Oxygen isotopes in nature and in the laboratory*, Urey summarizes the idea:

> The temperature coefficient for the abundance of the oxygen isotope in calcium carbonate makes possible a new thermometer of great durability, which may have been buried in the rocks for hundreds of millions of years after recording the temperature of some past geological epoch and then having remained unchanged to the present time. It is evident that, if an animal deposits calcium carbonate in equilibrium with the water in which it lives, and the shell sinks to the bottom of the sea and is buried securely ..., it is only necessary to determine the ratio of the isotopes of oxygen in the shell today in order to know the temperature at which the animal lived (Urey 1948, 491).

Thus, out of an isolated experimental system of an isolated (if not, sealed off) nuclear research facility grew a soon to be pivotal geoscientific method, which was based on the flow of elements in an open system: stable isotope geochemistry.

Nevertheless, “the first problem in the application of this method to paleotemperatures is the construction and operation of very sensitive mass spectrometers” (Urey et al. 1951, 401). The modifications and improvements of the Nier-type mass spectrometer were mainly to stabilize the ionization irradiator by a solid power supply, reliable amplifier valves and better emission control modules (McKinney et al. 1950). In the case of the piston corer, it was mechanical engineering that determined success or failure, but now it was sophisticated electronics originating from war laboratories like the M.I.T. Rad Lab. The multiplied precision needed to profit from the tiny temperature coefficient – essentially only 0.0000007 atomic weight units by a temperature change of 1°C – is highly symptomatic of the post-war shift from mechanical or optical apparatuses to the controlled application of electronics (Rosol 2007, 77-86).

Still, Urey’s first experiments with marine sediments encountered more mundane problems and initially turned out to be a “fiasco” (Hsü 2004, 184). Different species, originating from different ecological zones within the water column, that is, benthic and pelagic organisms, were mixed in the fossilized layer of calcium carbonate. No meaningful paleotemperature could be derived from this conglomeration of different marine environments. To solve this problem of mixed fauna and to bring in micropaleontological knowledge and practice, Urey hired the Italian Cesare Emiliani for his Chicago lab. Emiliani’s painstaking work in separating the species eventually led to the breakthrough. Shortly after Urey had, together with his colleague Stanley Miller, proven that life on this planet could have been originated from anorganic components (the famous Miller-Urey experiment), Emiliani was able to publish a paleothermometric graph correlating with the glacial-interglacial cycles of the last 290,000 years, covering basically the same time period as Schott’s graph of three years earlier while applying the decisively different quantification method of stable isotope spectrometry (Emiliani 1955, graph on 569). This method was subsequently refined, finally demonstrating the periodic fluctuations of ice volumes over millions of years that

Milutin Milanković had already calculated and explained by orbital cycles some 25 years earlier (Shackleton 1967; Milanković 1930).

Such is the admittedly very rough sketch of the fusion of nuclear chemistry and oceanography, and hence the beginning of modern ocean-based paleoclimatology that leaps beyond classical land-based Quaternary geology. Now, one would certainly expect that the entry of nuclear chemistry into the conglomeration of paleoclimatological methods came not without disciplinary disavowal. Yet, the intrusion did not seem to alienate the predominantly geologically or geographically trained paleoclimatologists. If the memoirs of the physical chemist G. J. Wasserburg are anything to go by, it was rather the opposite. According to him, the "real creative work" in establishing this method was done by the pioneering geochemists and not the geologists, "who were trying to grasp control of this intellectual and technical revolution" (Wasserburg 2003, 9).

A reason for the open attitude towards geochemical methods might be the traditional entanglement of classical geochemistry with geology itself, which I described above. But more than that – and Wasserburg's words should not bloat the "revolutionary potential" of isotope geochemistry in this regard – the nuclear chemists did not devalue the qualitative heuristics of paleoclimatology but instead strengthened them. Fusing the old concept of the stratigraphic column as bearer of fossils and, hence, geological time, with the explanatory framework of elementary cycles isotope chemists were able to invigorate both, while re-equipping hem with highly different technical means, indicators, and charts. By designing and tinkering with electronic equipment, earth has become quantifiable in a new metric, namely the isotopic signatures of geochemical flow, aligning and correlating the planet with a well-controlled experiment in the laboratory. In the end, isotope geochemistry has helped to entirely blur disciplinary categories such that today "the boundaries between geophysics, geochemistry and geology are indistinct" (Oldroyd 2009, 395).

4. Conclusion and Outlook

As has been shown, the seed of the general shift from a more or less constant, geographically determined climate to abrupt changes on a planetary scale was already planted during the oceanographic deep-sea expeditions around the turn of the twentieth century, without reaching real deep-time horizons. Hauling longer and longer cores from the ocean bottom revealed distinct layers of sediments, disputing the held belief that the deep sea is a tranquil scene exhibiting the endless deposition of relics of a persistent climate. In contrast to a predominantly geographical climatology early twentieth century oceanographers could already "see" climatic transitions in the profiles of their sediment cores, an insight that was continuously refined by establishing a firm biostratigraphic method. Contrary to what would be expected, the transfer to isotope methods after World War II did not change considerably this recognition in its heuristic quality, but rather expanded it considerably in terms of resolution of detail and thus the hope for direct causal explanations. In fact, this increase in quantitative resolution likely contributed to a qualitative shift in the sense that a search for not only patterns but mechanisms in paleoclimatic change could be dared and hence the search for geological analogues. Nevertheless, the absolute limits in chronological resolution of deep cores – e.g. bioturbation, that is the mixing of sediments by benthic organisms, prevents, on principle, a finer resolution than a few thousand years for the Eocene – plus today's understanding of the general incommensurability of climatic periods have again shattered this hope, as we have seen in the first part of this paper. The deep past remains noisy.

What this brief historical excursion into the prehistory of today's exploration of deep-time events has shown, though, is how modern paleoclimatology has aligned itself with a long tradition in oceanographic surveying and sampling, ready to absorb seemingly outlandish methods like the lab-style fractionation of isotopes. Emiliani's success in applying Urey's idea of the derivation of paleotemperature profiles by measuring isotopic ratios in the stratigraphic column is fundamental for today's deep-time paleoclimatology. Eventually, it opened up the way for internationally financed marine geological surveys, missions like the "Deep-Sea" and later "Ocean Drilling Program" (DSDP and ODP), allowing to bore deep into the records of the Cenozoic. The cores drilled in this way made deep-time events like the PETM readily available, a record of catastrophes that came to light with the aid of sophisticated mass spectrometry, data infrastructure and modeling.

Paleoclimatology is a very peculiar "interdiscipline" that historically rests on the blurred distinction between empirical observation and physical laws, a set of heuristical strategies and highly different material practices, especially with respect to the processing of data. Therefore, I am very skeptical about the applicability of the notion of a paradigm shift to paleoclimatology. If one would like to speak of a biostratigraphic paradigm – lasting, say, from the advent of paleontological reasoning by correlating fossil remains until the counting of foram species – how would that have shifted with the advent of isotope geochemistry? Biostratigraphy is a valid and vibrant method even today, along with chemostratigraphy, magnetostratigraphy, lithostratigraphy etc.

Nevertheless, while I argue against the concept of Kuhnian paradigm shifts with application to paleoclimate science, the point here is also not to revel in the steady progress of a "normal science." Instead it argues for refreshing the recognition, that the central heuristics of fieldwork present an astounding continuity, more often than not leveled out by the variety of its methods. The stratigraphic principle in paleoclimatology has never lost its appeal, regardless of whether the sedimental record has been disturbed by bioturbation, tectonic movements, or turbidity currents – all of which is another story on itself. Neither the shift from microscope to mass spectrometer, nor from Brooke's deep-sea sounding apparatus to the piston corer, revolutionizes the very heuristic core of what constitutes empirical data. In principle, the PETM as a geohistoric event is visible both to the naked eye and to the mass spectrometer.

That is not to deny but rather to support the fundamental agency technologies play in shaping the paleoclimatic rationale as a rationale of data processing. The pivotal element of declaring something in earth's history – namely a discontinuity in the sedimentary strata – as an event is intrinsically bound to certain technical apparatuses and infrastructures of excavating, transporting, storing, and analyzing. In principle, the more or less causal relationship between a given proxy and a climatic variable is always established by the mediation of some sort of technical instrument, while the virtue of that data is construed by a technical architecture of pedantry. In order to determine the epistemic load of a discontinuity found within the stratigraphic column, a fingerprint of an ancient climate transition, one needs to process it with a certain media technique or media technology, whether material or immaterial, *in mechanico* or *in silico*, that forges the link between the known and the unknown.

Nevertheless, the general epistemic idea and the heuristic quality of something like a "geohistoric event" that is somehow "recorded" – a media technological term par excellence – stays astoundingly the same, from Lyellian to Lovellian times. What differs are the concrete practical means that form the basis for the operational, mental, and social deployment of such terms as "event" and "analogue." Today, the technical transfer of the "stinking black mud" into the realms of numerical values by the use of mass spectrometry makes the "records" comparable, ready to suggest the existence of a geological analogue. As with all media technology, the signal to noise ratio is all that counts. Detecting a signal among the noise by painstakingly transcoding, filtering, and, yes, informed guessing, is the only way for science to decide whether the deep past is something that is awfully close.

Indeed, it is only the shift from one data technology to another that makes the above-mentioned difference. In the spirit of semi-empiricism an emerging new technique basically changes the means and portfolio of data patterns that can be created. In the end, it is these patterns that allow for a justification of not only the local definition of what constitutes an event in earth's history but also the discussion of their comparability, that is, the possibility or impossibility of geological analogues to present experiments in the "vast chemical laboratory" called earth. Here, indeed, the technological shift is at work epistemically, namely in the explanation of climate change in terms and in the vocabulary of signal processing and applied systems theory (e.g. discontinuity, noise, perturbation, thresholds, instability, filtering, etc.) that together form the conditional or epistemic basis for computer experiments on geohistoric events, being descriptive, explanative, and speculative at the same time. While "the modern view of abrupt climate variation as an emergent property of a complex system owes much to this advance in higher resolution paleoclimatology proxy records" (Snyder, Mastrandrea and Schneider 2011, 479), this semantic framework of knowledge production needs itself an explanation – something to be accomplished in a different paper.

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