Design at the time of the Anthropocene: reporting from the Critical Zone

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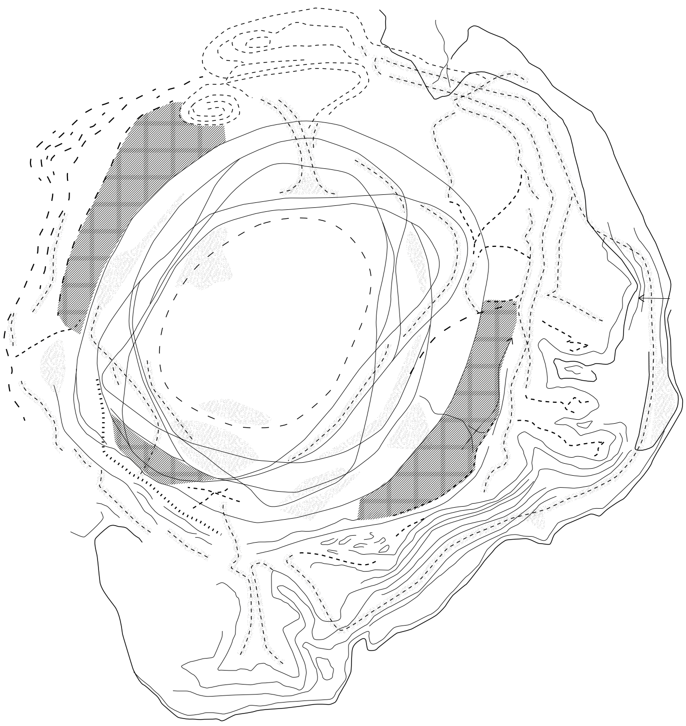

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List of figures

List of acronyms

AGU = American Geophysics Union
CO_2 = Carbon dioxyde
CRITEX = Challenging equipments for the temporal and spatial exploration of the Critical Zone at the catchment scale
CZ = Critical Zone
CZO = Critical Zone Observatory
GH = Gaia Hypothesis
IPGP = Institut de Physique du Globe de Paris
NCR = New Climatic Regime
OBSERA = Observatoire de l'eau et de l'érosion aux Antilles
OHGE = Observatoire Hydro-Géochimique de l'Environnement
OZCAR = Observatoires de la Zone Critique : Applications et Recherche
ZKM = Zentrum für Kunst und Medien

Notes on figures :
Most of the photographs are by the author. When mentioned, some are taken from video stills provided by Sonia Levy during the collaborative work on the 'Critical Zones' exhibition that we did together (see references of the exhibition in appendices).
Most of the drawings are by the author, with the exception of those by the scientists who have given their permission for their use and publication.

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Abstract

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The environmental crisis changed considerably the daily practices of landscape designers at the time of the Anthropocene, renewing attention to granular elements such as chemicals, sand, nutrients, water, earthworms, fungi, etc. The habitability of our planet depends on these various entities and their entanglement. With the "intrusion of Gaia" (Stengers), two visions of nature collide: the anthropocentric view, which perpetuates an idea of nature as a passive body, a background of human activities, and the cosmopolitical view, whose approach aims to better understand this intrusion of Gaia. This thesis first identifies which ideas, tools, designs and visual regimes contribute to perpetuating an anthropocentric vision of nature, and which ones, conversely, construct the cosmopolitical approach, through the variability, the agency, the complexity and the plurality of natural entities. However, this approach is yet to be developed. This is why this thesis aims to bring new, cosmopolitical insights into what a landscape is, what composes it.

To address these questions, I have undertaken empirical fieldwork using ethnographic methods, following scientists of a specific branch of earth sciences called the Critical Zone (CZ). The specificity of CZ science is the instrumentation of landscapes. In observatories, geoscientists decompose landscapes, through their observations of the soil, the rivers, and the atmosphere. This thesis examines how scientific instruments and practices monitor various natural features over the long term, in order to trace their unexpected trajectories. The dissertation shows how this knowledge can bring a new understanding of territories and the Earth, more attuned to the different cycles and their overlapping dynamics.

The thesis also experiments with alternative mappings to capture the complexity of the composition of the Critical Zone. These maps, or visualisations, shift the anthropocentric view (which divides the territory and visualises it as a surface to be constructed), to a cosmopolitical view (a view from within, which deconstructs the traditional cartographic frame of reference to create a new one that takes into account the depth of the soil and different cycles). The contributions are twofold: a more nuanced knowledge of what is called 'nature' through visual tools, and the production of meticulous cosmograms related to the scientific object Critical Zone. It is this ensemble that can be named 'gaia-graphy'. The production of these maps contributes to a better understanding of the dimensions of this Critical Zone and can bring a new understanding of landscapes in architecture. It can also have an impact on architectural practice and its transformative agency in the new climatic regime.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright Statement

Acknowledgments

I am grateful to all the scientists for their generosity towards me, tirelessly introducing me to their research and willingly taking me to their field. Travelling to the field was sometimes difficult, but none of the scientists made me feel alien or unsuitable, on the contrary, they were always kind and thoughtful. Even when they were in the middle of an action, they took the time to explain what they were doing. I never felt lost in the field and for that I am very grateful for their sense of community. The trip to the West Indies, and then to the Strengbach CZO where I found the same generosity, changed the game for me: I was not 'studying' the scientists from outside, I was part of their team, trying like them to make sense of the Critical Zone in my own way. Once you enter the CZ community, you are part of it.

Dedication

This thesis is dedicated to all those who care about Gaia, to the people I have met and who have gradually helped shape my new practice as a gaiarchitect. Most of them fill these pages with their thoughts, inspire me, provide me with new avenues of reflection. Starting with Bruno Latour, who introduced me to Gaia, answering my questions and disorientation, challenging us with his ideas and imagination. I am grateful for the chance to exchange with him and to draw the ever-changing shape of Gaia. I thank my supervisors, Albena Yaneva and Stephen Walker, for their support over the past three and a half years... due to unexpected circumstances! Albena for her guidance throughout the process, allowing me to make sense of the fieldwork and to get closer to a profession I would like to pursue in life. Stephen for his openness, care and imagination. I thank my ANT colleagues, Brett, Demetra, Fadi, Ben, who provide me useful advice and with whom we exchange thoughts and methodologies during the ANT seminars organised by Albena, which provide great writing sessions. I am grateful to Kim Forster for his readings in the early stages of the thesis and to Lindsey Bremner and Stefan Bouzarovski, who offered me an interesting and stimulating discussion in the final stage of the thesis during the oral examination. I thank the Terra Forma team and beyond, Axelle Grégoire and Frédérique Aït-Touati, Sonia Levy, and Jérôme Gaillardet, for their ability to drive me into uncharted lands! I am grateful to Michael Flower who edits the final version of the thesis. Finally, I thank my family, my friend, my partner, Soheil Hajmirbaba, a guiding star to navigate together on the waves of life.

To Shams, for his discovery of the Earth.

Prelude

When I first heard the term Anthropocene, three years before the beginning of my thesis, I was working as an architect in a landscape firm[1] on urban projects, parks, and territorial strategies to plan the renaturation of 'ruined' territories for future development. The work consisted in imagining a combination of conceptual and formal structures and tactics[2] to allow nature to flourish. For example, by allowing accidents to happen in urban rigid frames: the 'natural' flow of water, or the 'natural' formation of slopes, or the 'natural' progression of afforestation. We were working mainly on ruined soils and damaged landscapes, which I would later understand as the consequences of the Anthropocene. I first heard the term Anthropocene at the Theatre des Amandiers, during an experimental event, a COP Simulation, organized by Bruno Latour and SPEAP, called Make It Work[3], in June 2015. I was overwhelmed by the scale of the climate challenge which was far beyond the scale of the design projects I was working on. This leap across scales, from a site to the planet, was so destabilising that, for me, my practice as an architect no longer made sense. The term Anthropocene means that humans have become the main geological force, by modifying the environment. This modification of the environment challenges what is at the basis of architecture and spatial planning and forces us not only to rethink the tools of architecture, but also to open a dialogue with other disciplines. Consequently, I resigned from the firm and started to be interested in other forms of practice and in research, first through the SPEAP program with Latour and then thanks to this PhD.

Another shortcoming that I experienced in my practice was the use and capacity of the representation tools we employed to visualise a territory. With the cartographies, mostly inspired by Google Earth, we were only mapping the surface of the land. But often, in ruined lands, the project needs to

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1 BASELAND 2009-2016
2 I use 'tactics' according to the philosopher François Jullien (*Vivre de paysage ou L'impensé de la Raison*, Gallimard, 2014): tactics, bias, which he uses to describe the way Chinese ontology approaches the concept of nature. In my former company's landscape methodology, we also used this term to describe three ways of approaching a site: tact, intact, contact.
3 François Gemmene, during the COP Simulation in June 2015, organized by Bruno Latour and SPEAP.

visualise the underground to address the issue of soil pollution. For designers, this required new tools to render visible the content of the soil and what would be needed to improve its condition. I first became aware of this issue while working on the project of the Chemical Valley at Baseland in collaboration with OMA (Baseland, OMA, 2015). The Chemical Valley is an industrial-geographical entity along the Rhone in the South of Lyon, named after the industries stretching along the river. We were asked to develop a 'new nature' on these lands. But below the surface of the industrial platforms, soil simply didn't exist. This territory is built with rubble and other inert materials upon the old meanders of the river. This is in fact not a soil, that is, a layer formed by the slow weathering of rocks, as Zalasiewicz describes in his wonderful book *Rocks, A Very Short Introduction*[4]. I wondered what caused so much ruined lands. Here and there, wastelands conquer lands, replacing modernist productive factories with ruins and excavated materials that crack, burn and fissure the surface. The project in Lyon was aimed at producing new soils, fertile soils. New processes with scientists and industrials were invented and tested, and they are still in experimentation. This project triggers further new questions for me. Here, nature is either a resource or something to construct and encourage. I started to question the nature of 'nature'. Do we have a full account of what is nature? The notion of nature with which we were working seemed restrictive to me. At the same time, I discovered the work of scholars such as Donna Haraway, Emmanuele Coccia, Anna Tsing, Eduardo Kohn, Isabelle Stengers, Vincianne Despret, Bruno Latour, who destabilise further my thinking of nature as a single entity.

I was then introduced by Bruno Latour to the Critical Zone and the network of scientists elaborating new ways of doing Earth sciences. I became interested in their research as they could bring new ways of understanding what is nature, in ways more suitable for grasping environmental issues. I tried to involve my fellow architects, testing the need to introduce the Critical Zone science to landscape design. But I faced a rather strange reaction: "Oh! So this is an impact study, but at a bigger scale!"[5]. I was disconcerted: does bringing the Critical Zone to design studies really matter?

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4 The author studies stratigraphy, the evolution of the earth and its rock components, where everything is inscribed in the petrified movements of rocks.
5 Personal conversation with the director of Baseland landscape firm.

Is there a need here or do landscape studies already know everything that is useful for them? That was contradictory to my intuition. This led me to begin a dissertation that aims at deepening our knowledge of the Earth and then bringing it back into the field of landscape studies. I am convinced that what happens in science is closely related to landscape design and vice versa.

1 Introduction

1.1 The Anthropocene: uncertain times

Every new Intergovernmental Panel on Climate Change (IPCC) announces a new figure for Earth's rising temperature (at least +2°C and possibly +7°C) and the catastrophic consequences for the planet's environment and people. Floods, droughts, storms, sea-level rise and soil erosion will cause dramatic social and political upheavals. This will result in a New Climate Regime[6] (Latour, 2017a) or a new "climate of history" (Chakrabarty, 2009) as these changes will trigger intensified transformations and lead to socio-political changes, which some scholars in the humanities declare a "cosmological paradigm shift" (Latour, 2019; Vivieros de Castro, 2019). These transformations are already taking place, as evidenced by land degradation and biodiversity decline seen with the expansion of ruined landscapes: wastelands, abandoned industries, climate-damaged sites. Nature is no longer perceived as a stable entity, rather it is changing rapidly. Even more worryingly, the quality of life on Earth is threatened by the destruction of living assemblages that have so far maintained the habitability of the Earth, for humans and non-humans alike. As Tsing points out, landscape refers "to material enactments of space and place by many historical actors—human and non-human." (2019:136). As the human population increases, we are concerned about resources and depletion. The most significant change in natural history today is the arrival of the Anthropocene, which can be understood as the decomposition of landscapes. Thus, as Tsing asks: "How can we best use our research to stem the tide of ruination?"

The Anthropocene is a term that helps us to understand these ruinous transformations. It was coined and is used by Earth scientists (Crutzen, Stoermer, 2000; Rockström, 2009) to define this New Climate Regime, this transformation of nature. Although the Anthropocene has given rise to very lively discussions in other fields, such as in the humanities

6 The term New Climatic Regime (NCR) is the title of the book *Facing Gaia*, a compilation of eight lectures by Bruno Latour on why we should consider nature differently and replace it with Gaia, a scientific hypothesis developed by Lovelock in the 1970s (and which will be explained later in the thesis). The value of using the term NCR is that it emphasises that we are in a different climate; we are not facing a crisis (which is by definition temporary) but rather the need to adapt to a new world, namely the Anthropocene.

(Chakrabarty, 2009), history of sciences (Bonneuil and Fressoz, 2016), philosophy (Hache, 2014; Stengers, 2015; Haraway, 2016), anthropology (Descola, 2017) or ethnography (Tsing, 2017), it seems that design studies have still shown little interest in the debate on these issues, except for a few attempts (Turpin, 2013; Ellsworth and Kruse, 2013; Tyszczuk, 2018). This situation needs to be rectified. To understand these transformations of nature, the environmental, spatial planning and architectural studies are called upon here to mobilise their efforts to bring about a new conceptualisation that would better describe these changes and thereby adapt their methodologies and tools to cope with this New Climate Regime.

Indeed, the Anthropocene introduces instability into our traditional conceptual framework and design practices. Spatial and temporal scales (local / global; seconds / million years) are totally disrupted and are no longer understandable through human commonsense experience (Grosz, 2013; Moss and Galison, 2015; Stengers, 2013). This is why we can suggest that theories and practices are torn between two competing ontologies or worldviews that are in dispute, both conceptually and visually, supported by two different modes of visualisation and the techniques to produce them, modes that conceive nature in different ways.

The first view considers nature as a passive object that the human subject is actively dominating. This is the *anthropocentric view*, which is still dominant, and which is based on a conception of space dating from the 18th century, where nature is out there, a background pre-existing human activities, a stable environment. In this perspective, nature is a resource to be extracted, non-human voices are silent, de-animated and part of an economy of ecosystem services (L.MacHarg, 1969). The visualisations associated with the anthropocentric view are satellite imageries and maps that are drawn for purposes of exploration and land appropriation. This view is criticized by many authors (Stengers, 2015; Haraway, Tsing and Olwig, 2016; Farinelli, 2009). The critics point out that the notion of space, in this view, is taken for granted (Latour and Yaneva, 2008; Heyden, 2013), as is the way maps that are drawn (Grevsmühl, 2016; Brotton, 2013; da Cunha, 2018). And that is a problem because it may have contributed to the forces and practices that produced the Anthropocene and the assumption that nature is a passive 'décor'.

While in the anthropocentric view nature is a backdrop to human activities, the *cosmopolitical view* recognises the variability of nature, and that it is composed of a great many humans and non-humans, all of whom are active. This alternative perspective emerged from science and technology studies during the 1990s (Stengers, 2010; Latour, 2013) and is now being updated by researchers who are providing new insights into nature (Tsing, 2015; Debaise, 2017). From this cosmopolitical perspective, landscape is a living and complex assemblage. While the anthropocentric view perpetuates the passivity of nature, the cosmopolitical view, close to the concept of Gaia, a scientific hypothesis from the 1970s (Lovelock, 1979, Margulis, 1998; Dutreuil, 2016), argues that nature is anything but a passive and peaceful backdrop. We are caught up in its activity. As Latour reminds us, emancipation does not mean "freed from bonds", as in the anthropocentric view, but means to be "well-attached." (2005:218). Similarly, Gaia asks us how can we be well-attached? How can we make the world cosmopolitical? In this view, shifting assemblages of living and non-living beings who constantly adjust themselves to changing conditions, generate a form of regulation of the Earth, a continuous "maelstrom" that animates landscapes. However, the field of architecture and landscape lacks a comprehension of this complexity and the legacy of Gaian theory. The second chapter of this thesis will elaborate these two contradictory views and their consequences. But first, we need to explain why our study of the Anthropocene relies on a term unknown in the field of architecture: the Critical Zone.

1.2 Focusing the study on the Critical Zone

The Anthropocene shakes up the way we understand the composition of nature. Therefore it is important to trace and analyse this new composition as a mediated and composed reality. To grasp the scope of the Anthropocene, we can trace natural processes by following human and non-human entities in particular places. To do this, we can rely on natural sciences which observe anthropogenic nature. Hence the choice to focus the fieldwork of the thesis on Observatories of the Critical Zones (OCZs) where an alternative understanding of nature seems to be more clearly visible. Indeed, to localise the study of these transformations, an emerging community of geoscientists is working in CZOs around the world. Coming from different disciplines (geochemists, hydrologists, soil scientists, seismologists, ecologists), the scientists focus on environmental problems at the Earth's surface by analysing the complexity of the cycles that occur at the intersection of soil, atmosphere, water and rocks. The scientists share in the study of local observatories that range in size from a few hectares to several square kilometres in large watersheds. The Critical Zone (CZ) is not the whole Earth - or the globe - but the thin layer on the surface of the planet where human and non-human beings live. This is the area between the "deep rocks and the upper atmosphere" on which all activities are concentrated and where soils are threatened. This zone is therefore critical in many respects. It is one of the main interfaces of the planet and although it is known to be fragile given human impacts (Brantley, 2017), it is still poorly understood. By providing a territory for studying changes, CZs can help us to develop an alternative understanding of nature by tracking its movement and variability. Indeed, CZ scientists follow the trajectories of chemical components which leave traces as they transform themselves and thus modify the facies of landscapes.

Thus, CZ is an empirical lens to make nature and landscape observable, allowing us to witness its composition as a heterogeneous process (a combination of various sites and entities around the Earth) made of hybrid elements (instruments, biogeochemical tracers, imageries). As noted earlier, the entities composing "nature" are often seen stable, static, invisible, and taken as a block separated from human world. This thesis contributes to the understanding of the CZ as composed nature, as a process constantly negotiated by humans and non-humans alike, living and non-living, as trajectories always on the move. The CZ can be considered in part as a response to the Anthropocene, a local *and* global one, monitoring events with vertiginous *and* limited dimensions, from microseconds to billions of years.

1.2.1 Aims and objectives

Given the importance of the Critical Zone, the aim of this dissertation is to answer these questions: what is this new understanding of nature that is emerging through the Critical Zone Observatories? How does it change the way we understand and even design landscapes? Does it therefore change the way we should visualise territories and how?

To address these questions, the study adopts a pragmatist approach that traces the key entities of the CZ as it unfolds through their scientific discovery. To do this, I have conducted an ethnographic inquiry into the network of Critical Zones Observatories.

The first objective was to shadow the scientists studying the Critical Zone. I was specifically interested in the scientists because they are the ones who gain new knowledge of nature: they study geomorphology, water circulation and chemical exchanges—the circulation of carbon, nitrates, phosphorus, sulphur, either activated by microorganisms and bacteria or disturbed by human activities such as agriculture or industry. They install instruments in the landscape, extract measurements, and collate the data in their laboratory to better understand the processes. As the first landscape architect and observer to position myself within this type of external laboratory, I have been able to record the internal movements of these flows.

The second objective was to trace the role and use of instruments set up in a CZO by the scientists. The instruments allow the scientists to ask questions and to obtain answers to those questions in a cognitive regime. It is therefore a way for them to extract and acquire new knowledge on all these processes and to extend their knowledge on chemical flows, flows of microorganisms, temperature changes, and levels of pollution. The Observatories study at different depths and heights the multiple phenomena that shape a landscape: air turbulence, seismic movements, chemical transport of pollutants in different compartments of the earth, electricity in the soil, exchanges between roots and fungi, chemical transport of tree molecules by leaves, wind speed and much more. The instruments have a certain power or agency because they enable scientists to get access inside this cosmos.

1.2.2 Visualisation of the Critical Zone

As I remarked previously, the drawing / visualisation techniques / modes of representation we are accustomed to using belong to a different ontological approach (the anthropocentric view) and are part of the problem. During my fieldwork, I have also understood that scientists of the CZ face a problem of visualisation of their own object of study. In their conventional representation of the CZ, scientists still rely on an image—the globe—that does not help to see the CZ, which is actually a very thin layer on its surface. Similarly, cartographers rely on the latitude/longitude system that obscures the different soil layers and their interactions, by flattening, superimposing and confounding each of the layers with others. Thus, these cartographies do not allow us to see the Critical Zone, freezing landscape entities into one state and excluding their changing states. Producing complementary and alternative visualisations would help us to understand the complexity of nature portrayed by scientists' capture of tracked flows, pollution, migration of microorganisms, etc.

Therefore, to provide better understanding of nature, it is important to renew the modes of visualisations we use. Indeed, to visualise the various entities involved in the transformation of landscapes in the Critical Zone would mean being able to understand and grasp this complexity by describing the instruments and the techniques that produce the visualisations which support ontologies (Daston, 1992; Galison and Daston, 2007). Indeed, powerful visualisations have stabilised an anthropocentric view. How then to produce cosmopolitical visualisations? In order to trace movements of the variability in nature that we are witnessing from a cosmopolitical perspective, we must bring together in one visual space both humans and non-humans, their discourses, and also their ontological differences. This visualisation should not define *a priori* boundaries between actors, but follow how they overlap, as suggested by Actor-Network Theory (Latour, 2015). The task of visualisation is therefore more than just a representation of reality, it is also the manner of our constructing the reality. We can also call this new form of representation a *cosmogram* after Tresch (2005; 2007); that is, a visualisation that embraces the entities, their relationships and the ontological layers that are attached to them. The last objective of this dissertation is therefore to produce new kinds of visualisations that will trace trajectories of components such as molecules responsible for environmental damage in a particular observatory. For this purpose, I have followed all the actors to which the agent is attached, thereby creating the specific associations with human industries, the atmosphere (O_2, H_2O), the soil, roots, bacteria, or rocks that lead to landscape transformations and disturbances. The objective here was to understand how components cause environmental damage when their cycles are disrupted and to produce visual versions of these trajectories. By seeing well inside the strata of landscape through which an agent passes, it is possible to locate the global processes of change and through the generation of alternative mapping techniques to capture the complexity that scientists experience within the Critical Zones. Drawing on previous research (Arènes et al., 2018), I have produced visualisations that do justice to this complexity. For instance, by proper reporting and visualisation of biogeochemical phenomena, human impacts on cycles will no longer be seen as an independent layer superimposed on other geological and biological phenomena, but rather appear for what they are geochemically in the Anthropocene: exchangers, switches, shape changers, cycle exchangers. These visualisations provide tools to trace and therefore understand and imagine the transformations that occur in the Critical Zone. This better understanding of natural processes resulting from mapping techniques can be called “Gaia-graphy”. The term gaia-graphy emerged from Latour’s reflection on the nature of Gaia related to space and how Gaia changes the way we should understand space: “Gaia subverts the levels. There is nothing inert, nothing benevolent, nothing external in Gaia. If climate and life have evolved together, space is not a frame, not even a context: space is the offspring of time.” (2017a:106). The practice of tracing space, of -graphy, remains essential to Latour but instead of the prefix geo- we should prefer the prefix gaia-[7]. The full extent of the term gaia-graphy has then been developed in a paper

7 “With these hybrid terms, scientists are inventing a geo-tracing activity, which only reminds us, after all, of the old meanings of geography, geology, geomorphology – that is, the writing, the inscribing, the tracing, the mapping, and the inventory of a territory. No one can belong to a land without these activities of tracking space, marking plots, tracing lines, activities identified by all those Greek terms – nomos, graphos, morphos, logos – that are rooted in the same Ge, Geo, or Gaia.” P275

that I wrote with Gaillardet and Latour to refer to a visualisation framework which would grasp the nature of Gaia. A Gaia-graphic view shifts « from a planetary vision of sites located in the geographic grid, to a representation of events » (Arènes et al. 2018). After these visualisations are developed in what follows, they will be returned to and discussed later in this thesis in the field of architectural studies to inform architectural understandings of nature, to better inform planners of the extent of landscape transformations caused by climate change, and thereby better equip them to act accordingly.

1.2.3 Reporting from the Critical Zones

Following an ANT pragmatist methodology, the project will trace non-hierarchically human and non-human entanglements. The aspects and history of this methodology inspired by ANT and STS are developed in the chapter on methodology. In this summary, I briefly outline the fieldwork and some of the methodologies used to collect the findings that constitute the empirical chapters.

Outdoor labs: the Critical Zone Observatories

The most important findings of the fieldwork were collected directly in the field and from landscape throughout the network of the Critical Zone Observatories (the national scientific infrastructure for France called OZCAR). Five different observatories at varied scales have been selected: a forest impacted by acid rain (Strengbach, Vosges, France), a semi-rural landscape with pesticides problems (Orgeval, Ile de France), two watersheds with fast erosion processes (Guadeloupe, French Antilles, and Puerto Rico, USA), and a karstic region (South of France) with water depletion issues. I spent 2 to 3 weeks in each of these empirical observatory field sites where I followed the scientists as they went about their work. Thus, I have been the first architectural researcher to be placed in their world, which is not a confined laboratory but a territory. I witnessed how the instruments record the variability of the Earth, how scientific practices and procedures shift an understanding of the landscape from a background to something more active, dynamically involving a wide range of entities and phenomena that are not taken into account in Architecture. By tracing this constellation of scientists, I show how an observatory functions as a prototype laboratory in the field: how it is connected to the territory or, said differently, how it connects the territory.

Indoors: the Laboratories of the Critical Zones

The scientists don't work all the time in the field but go back to laboratory buildings to analyse their samples, records, measurements, etc. I myself was allocated a desk at the IPGP (Institut de Physique du Globe) in Paris for three months. My fieldwork at the IPGP provided the opportunity for helpful discussions with the scientists who work at these different observatories. I came to understand how the landscape is literally decomposed and how the process of tracing tiny particles and other elements of the CZ is done, thereby producing findings about the terrestrial cycles of the Earth. At the IPGP the scientists of the CZ have made considerable progress in coordinating data collection, data standardisation and the modelling of many CZs around the world.

Five methods were used simultaneously during my fieldwork.

First, ethnographic observations were conducted at the beginning of my work at each field site. I went to the observatories with the managers and 2 to 10 other people (depending on the size of the observatory), where I collected an informal presentation of the terrain, traced the scientists' itineraries, and witnessed their relations with the site. This allowed me to follow them and the instruments they use to trace the complexity of landscapes. I then visited the laboratory buildings to find out how they extract the data from the field, how they process it and what images they use to circulate it.

Second, ethnographic field interviews were an extension of ethnographic observations. This type of interview occurred spontaneously in the field, when scientists wanted to help me understand their procedure, showed me the instruments, etc. This method offered a new perspective on how to approach a landscape, as the scientists follow a standard protocol from station to station.

Third, semi-structured interviews took place during ethnographic observations. They explored some aspects of what have been seen on the site. I asked scientists about their practice, the changes in the landscape they have observed, how they relate to invisible phenomena with specific instruments, and what are their particular attachments to the territory of which they are part. An interview lasted one or two hours.

Fourth, content analysis of scientific reports allowed me to collect knowledge on biogeochemical cycles occurring in a landscape observatory. But since the content is difficult to understand, I used a fifth method to get a more accurate understanding.

Fifth, I used my drawing skills to produce different versions of maps of the Critical Zone that allowed me to trace the trajectories of the cycles and to do this collaboratively. I submitted templates to the scientists which were then worked on with them. After that, I produced drawings on my own and then shared them with the scientists for their comments. By correcting, retracing, and adding information, the scientists' comments allowed me to better understand the processes that are a challenge to observation and representation. Drawing maps is both useful for synthesizing the amount of data and giving it meaning, but also for generating more quantitative data and for putting scientists to work. But more importantly, it is this method that gives meaning and understanding to the complexity of cosmopolitical view of nature. In concrete terms, this method has been tested with some scientists at the IPGP. A clean version of a map was submitted to the research director on which he started drawing the chemical cycles work. When he had doubts about a process, he invited other scientists to elaborate on the map, which they did. The collaborative work with maps produced a positive outcome: better understanding for how to gather, process and portray data. All these visualisations, once assembled, allowed the scientists and me to better understand what the CZ is or what it means to be in nature and to capture all these movements of the cosmos.

1.3 The structure of the thesis

This dissertation is organised in eight chapters. The first chapter is the introduction. The second chapter discusses the gaps of knowledge about Anthropocene in architectural research, and consequently the shift of emphasis from an anthropocentric view of nature to a more cosmopolitical view. It is the second view that is the focus of chapter 2, notably around the notion of Gaia and its intrusion. The third chapter describes at length the methodology used and the sites where the ethnographic observations took place. The three empirical chapters – chapters 4, 5 and 6 – aim to illustrate the decomposition of taken-for-granted Anthropocentric view of landscape entities such as soil[8], rivers[9] and atmosphere[10], and to show that they appear differently through the prism of Critical Zone science (of the scientists' instruments, procedures and practices). These chapters are thus organised according to these three entities, demonstrating the shift towards a much more cosmopolitical view of landscape.

Chapter 4 titled 'Soil' introduces us to the soil through the Critical Zone sensors that are installed directly in the field, such as geophones, gravimeters, piezometers, geological core samples. The first part of this chapter analyses how practices, procedures and instruments give scientists a view into the interior of the Earth: deep, inaccessible, dark and undefined areas of the underground. A different type of monitoring than that of satellites is carried out with sensitive machines anchored in the ground. Soils are observed at different CZOs under different climates and land uses. Depending on the depth of the soil—near-surface or remote, 'subterranean', different phenomena and features, connections and properties appear and allow for the decomposing of the unified view of the soil. In this chapter I argue that the methods of metrics and surface mapping used in architectural projects cannot capture the dimensions, plurality and variability of these soil layers. Other more tragic aspects that scientists also detect are not visible in these maps: the disappearance of soils, leaving ruined lands that we do not yet consider as such. The study of soil raises the question: how can we be more attuned to the 'Tidings of the Earth', its dynamics and its whispers?

Soil is mostly constituted by the action of water. Chapter 5 titled 'Rivers' follows the same development as the one on soils, this time focusing on water: the element that flows through the Critical Zone, transports elements and shapes rocks. This flow is recorded in a small architecture housing a high-tech laboratory in the middle of landscapes (forest, field crops),

8 In standard geoscience knowledge, soil is a mixture of organic matter, minerals, gases, liquids and organisms composed in layers onto bedrocks and which supports life on Earth.
9 A river is a usually fresh natural flowing watercourse from a source towards the ocean, sea or lake. Part of the water cycle, rivers collect water from precipitation through a watershed (drainage basin) from surface runoff.
10 Atmosphere is the gas layers of the Earth chemically composed to ensure life and protect the planet from solar radiation.

in CZOs. In this chapter, we discover how this lab-land could change the way we perceive a river, no longer in the singular but in the plural, no longer a line on a map but a vector of overlapping cycles of elements. Astonishing information can be extracted from a single drop of water, such as that which allows the uses of a land to be traced on a territorial scale. This chapter therefore clearly demonstrates this relationship between the micro and the macro, which is no longer conceived in terms of naturalization, but which shapes a new cosmology. Similarly, the temporalities, ages and memories of the earth are reconfigured when the sciences of the CZ are interested in rivers. This new configuration no longer places humans at the centre of nature, but rather envisions them as a disturbance in the Earth's dynamic system, a specific signature among those of non-humans, on the cycles.

From its deepest recesses, through and then upwards to its outer bound, the dissertation follows the layers of the Critical Zone. Chapter 6 reaches the top layer: the atmosphere, the most elusive entity in the environment. As in the previous chapters, we observe how scientists are developing strategic instruments to record chemical variations in the atmosphere and how these chemicals impact the habitability of the land. The atmosphere is indeed a fragile composition that we are used to considering as external. In the CZ, the atmosphere is tracked wherever it permeates: in the respiration of trees and, more unexpectedly, in the soil at depth. The trees, the forest, are the sentinels of these atmospheric variations, linking the vertical layers of the CZ, reacting to changes and informing the CZ computer models. The trees are the protagonists of the narrative here, along with a cohort of other organisms and elements, living in symbiosis or conflict. This chapter traces this process, how the forest adapts the environment to its needs by controlling CO_2 and water. At the same time, the forest becomes a network of sensors on the ground, which once again shapes the connection between local and global atmospheric conditions, affecting territories here or there.

The question of visualisation, raised in Chapter 2 in the literature review, is addressed in chapter 7, 'Mapping the Critical Zone'. First of all, it returns to our current representations and why they do not allow us to deal with the New Climatic Regime and more particularly with the manifestations of Gaia. Indeed, these representations adopt an anthropocentric view of environments, making invisible most of the entities that actively compose them. During fieldwork in the CZ, I translated my observations into visualisations. These visualisations help us to better grasp and make sense of the complex processes traced in the empirical chapters 4, 5, and 6. This chapter therefore develops a new set of frames of reference to replace anthropocentric ones. These alternative visualisations place the instruments in the maps, as if we were seeing the Earth from the inside with all the instruments deployed in the CZ. These maps follow the practices of the scientists, they are socio-technical, they deploy their cosmology, as do cosmograms. Because they bring together practices, instruments and entities, they are cosmopolitical; they show the diversity and number of things that must be taken into account in design. Moreover, using these new frames of reference it is possible to experiment with other maps to describe and draw the terrestrial cycles of a territory, precisely the subject of the Gaia hypothesis. It is for this reason that these maps can be called 'gaiagraphy', adopting a new reference frame based on the manifestations of Gaia in the Critical Zone.

The final chapter, 'Conclusion', summarises the results of the fieldwork developed in the empirical chapters: how the practices of observing with new instruments, decomposing taken-for-granted landscape entities, tracing the different elements of what composes the environment, and connecting new scales, spaces and times, change our perspective on nature. Secondly, the conclusion examines how this thesis contributes to filling the knowledge gaps identified in the literature review, regarding design studies' consideration of the Anthropocene. In particular, it raises the possibility of defining a process of cosmopolitical design which, following the recent emergence of this vision in the sciences and humanities, which promises to be more effective in addressing the challenges of the NCR and the intrusion of Gaia. The conclusion thus demonstrates how the results enrich the debate on the Anthropocene in architecture by extending it to the entities and strata encountered in the CZ, and how this extension articulates with the sciences and humanities. This in turn contributes to the construction of a cosmopolitical vision, and to the establishment of cosmograms as a means of shifting away from anthropocentric views to the development of cosmopolitical views. This development consequently contributes to the field of design theory, the advocating of ethnographic fieldwork, and the display of new dimensions in landscapes and new ways of approaching them through “unintentional design” and “unscalability—all this as we gradually become aware that we live in a ruined world where conditions of habitability are threatened. Therefore, the thesis directly addresses the challenges of Gaia and contributes to its recognition in the field of design, notably through the establishment of alternative mappings that capture the ‘breathing’ of Gaia, i.e. the earth’s cycles, their variations, and the way they are disrupted by human activities. This last contribution opens up new ways of conceiving the strategic development of territories, as well as ways of collaborating with the sciences and bringing them to the attention of stakeholders, designers, citizens and public decision-makers.

2 The Anthropocene and its views

2.1 Introduction

The state of the Earth threatens the conditions of habitability for every species. The planet has entered a new epoch where humanity is a major force capable of disrupting biogeochemical cycles and causing storms, melting ice, moving rocks, etc. This era is called the Anthropocene by some scientists. Others fear the «revenge of Gaia», the return of the reaction of the Earth to our excessive activities on it. The subject deserves to be addressed by design architecture, landscape or urbanism because cities would be partly responsible. The "Urbanocene" or "Urbicene" (West 2017; Lussault 2021; Angélil & Siress 2018; Williams, M., Edgeworth, M., Zalasiewicz, J. et al. 2019) stresses that the Anthropocene is caused by cities, by the fact that humans gather to live, work, play in dense agglomerations which produce a lot of waste, pollution, and lead to unsustainable lifestyles (transport of food, consumers, materials, etc.). Cities require the extraction and the exploitation of resources from other territories. The geologist Zalasiewicz (2020) even started to develop a method to calculate the weight of the city, its materials and pollution, in order to understand this phenomenon. Based on a scaling of the Earth in a volume of 1 cubic meter, he shows what makes up the Earth today: mainly man-made products and its waste that have overwhelmed the geo and biosphere.

The Anthropocene is a term that has spread rapidly from the earth sciences to other fields since the year 2010. It can be seen as a trigger for a critique of what could be called the anthropocentric view of nature, which has led us to this New Climate Regime, as coined by Latour. The other term that could also be used to describe the New Climate Regime, Gaia, is less known. However, it conveys a different approach in particular to understanding nature, which could be called a cosmopolitical view, and which could help us to refine the relationships between humans and non-humans and life on Earth.

In this chapter on literature review, we will begin by comparing the Anthropocene and Gaia, from their scientific origins to their diffusion or not in human sciences and design. In the second part, we will examine what the anthropocentric view of nature is, how it impacts landscapes and territories (causes and effects of the New Climate Regime), what the consequences are for design, and what types of visualisations of the earth perpetuate and diffuse this view. In the third part, we will study the cosmopolitical view in the same way. At the same time, we will identify the gaps that need to be addressed in the field of design to respond to the challenges of the New Climate Regime.

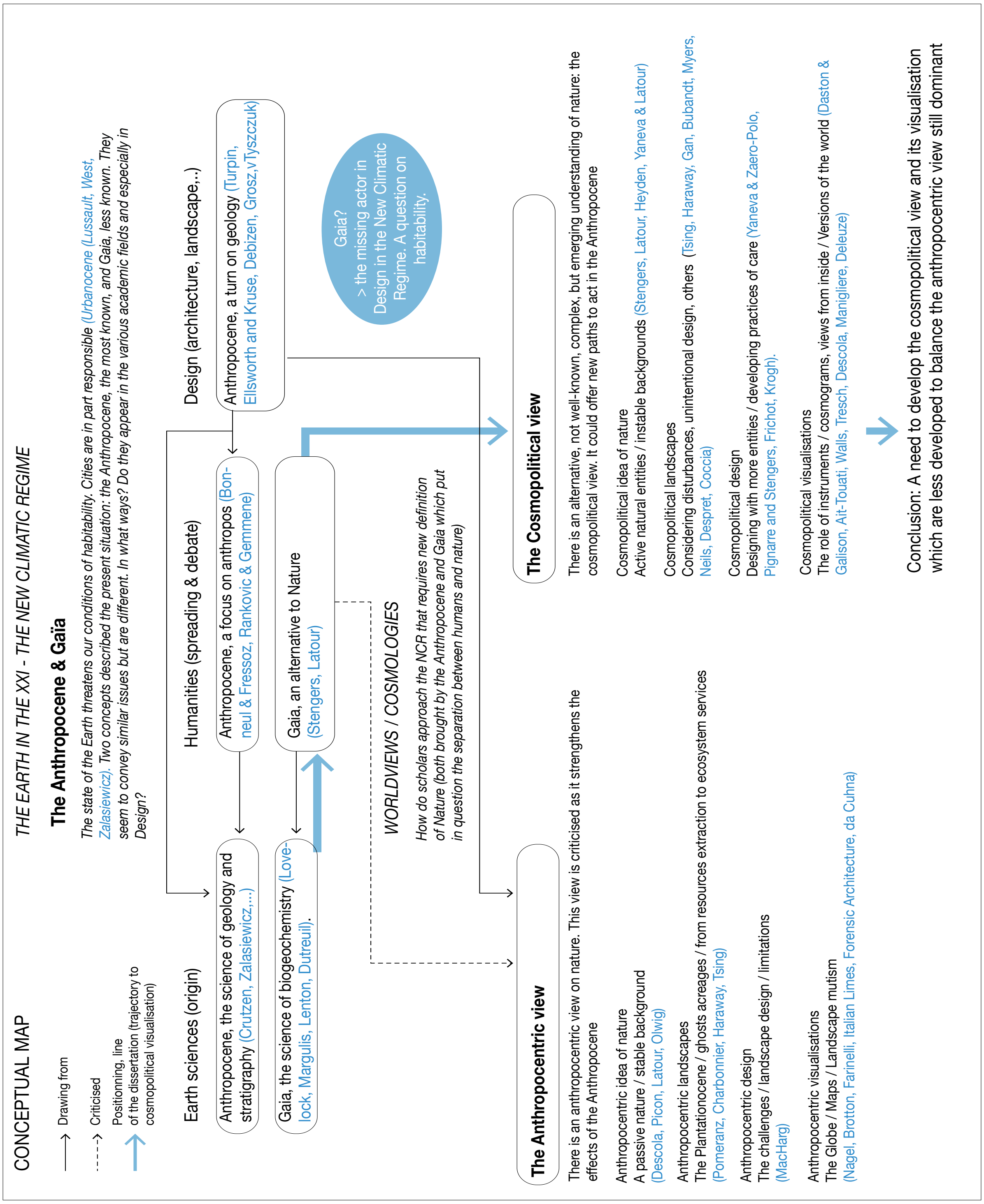

Diagram 1. Conceptual map of the literature review

2.2 The Anthropocene & Gaia in Earth Sciences

In this part, we will discuss the origin and diffusion of the term Anthropocene as it shapes important debates in different fields of science and humanities today. We will also discuss the meaning of a lesser known term that is nevertheless gaining attention in some circles for understanding the New Climate Regime we are facing: Gaia. First, we will give an overview of the origin of the two terms in the sciences, then, how they have spread in the humanities, and finally, how they have been understood in design theory at large.

The term Anthropocene originates from the Earth sciences at the turn of the millennium, not without controversy. It was suggested by a small working group of stratigraphers working to name the epochs of the planet (Crutzen & Stoermer, 2000; Crutzen 2002). With the help of Earth System Sciences (Rockström et al., 2009; Waters et al., 2016), they had come to the conclusion that it was difficult to say that we had remained in the Holocene, that fairly stable period in the history of the planet, during which humans had prospered under a favourable climate. The undeniable climate disruption shown in climate models, the discovery of new layers of plastic or radioactive particles in rocks (Zalasiewicz, 2015), as well as the accelerated disappearance of countless animal and plant species (incalculable because ecologists suspected that some disappear even before they are discovered), are all factors that no longer corresponded to the Holocene's trajectory.

The *Anthropocene Working Group (AWG[11])* chaired by Zalasiewicz is tasked with assessing what the clearest evidence is, from a geological perspective, that we are entering a new era. Their latest report, based on several previous articles (Waters, Williams, Zalasiewicz, 2019; Ellis, Snelling, Waters, Williams, Zalasiewicz, 2014) explains their methodology which consists in looking for 'markers' of the Anthropocene: what evidence, in events (invention of the steam engine, nuclear bomb), materials (plastic, nanoparticles, nuclei, etc), sites (lakes, rivers, sea floor, etc), can account for the Anthropocene: a change in the composition of the materiality of rocks, a change in weight, etc...

11 http://quaternary.stratigraphy.org/working-groups/anthropocene/
This group of thirty-eight people was created in 2009 by the Quaternary Stratigraphy Subcommittee (International Union of Geological Sciences) to determine the official periodisation of the planet.

The report mentions nuclear particles, plastics, new materials, phenomena like carbon pollution, or the construction of tunnels, earth displacement, etc.

Indeed, geology is based on stratigraphy techniques: what is in the rocks shows what is different from one period to another, that the Jurassic is different from the Cretaceous for example. We can read in the rocks the great floods that changed the landscapes, or the birth of vegetation in the Carboniferous, etc. These events mark periods, epochs, and ages. Compared to these time scales, the way human activities mark an epoch is very short in time, but the impact is unexpectedly strong nowadays, so that traditional geological rhythms and time scales are also disrupted (Zalasiewicz, 2010; 2016b). This is the Anthropocene.

The Anthropocene as a geoscience suggests a cumulative approach to understand the New Climate Regime, aiming to aggregate all kinds of material related to the epoch. Another version is the one put forward by biogeochemists, who emphasize the disruption of major terrestrial cycles.

Another approach is to consider the Earth as a system more or less in equilibrium, maintaining habitable conditions favourable to the organisms (fauna, flora, humans) currently living there (Lenton, 2016). A group of scientists at the Global Systems Institute[12] and Climate Change and Earth System Science at the University of Exeter, work on tipping points, Earth resilience and Gaia theory. This group of scientists uses the notion of planetary boundaries (Rockström et al., 2009): there are parameters that keep the Earth in equilibrium, but if they are disturbed too much, the system will run out of control and there will be no turning back (this is the snowball effect, or positive feedback loops). These parameters are largely the biogeochemical cycles. They aim at understanding how the Earth will react to the most disturbing human activities. Earth system sciences are in fact heirs to the Gaia Hypothesis.

The Gaia Hypothesis (GH) is an older theory than the Anthropocene, advanced in the 1970s by the geochemist Lovelock (1979; 1995) and the biochemist Margulis to understand the Earth: in this theory, the Earth is not passive and every living being has an impact on it. The extent of this impact will put the Earth out of balance, i.e. condemn its habitability. The GH

12 https://www.exeter.ac.uk/gsi/

is therefore a broader concept for understanding how the Anthropocene is changing the Earth. It also comes from a different discipline of earth sciences: not geology but biogeochemistry. In his PhD thesis, the historian of science Dutreuil (2016) explains that Gaia was also suggested as a name for the epoch, but as Lovelock was unpopular in academic science, the term was not approved, and the Anthropocene gained favour in the debate. Coined at the same time, GH seems to be just as important as the Anthropocene but seems to be much more complicated to understand.

In *Symbiotic Planet: A New Look at Evolution,* Lynn Margulis (1998) dedicates a chapter to Gaia. She explains that Gaia was born from James Lovelock's observation of chemical contradictions in the Earth's atmosphere: oxygen and methane gases are very reactive with each other and could not exist at the same time without being actively produced and maintained. Looking at Mars or Venus, Lovelock realized that there it was not the case: the gases were in stable equilibrium (stable atmosphere composed of non-reactive gases). He inferred that these planets were dead. What, on the contrary, would actively keep the Earth in this state? As a microbiologist, Margulis replied that the metabolic product of bacteria is methane. By reacting with oxygen, methane produces carbon dioxide. Moreover, while we know that the planet has cooled over the last 3 billion years, the sun has become brighter, warmer, and therefore it should have warmed the Earth more and more. Lovelock deduced that temperature and atmosphere were regulated on a global scale and suggested that it was life that sustained its environment.

Therefore, the core of the Gaia hypothesis is to prove that biogeochemical processes produced by living forms generate the environment. The environment is not pre-existing to organisms that would only insert into it and adapt to it (as suggested by post-Darwinians). Organisms would be much more active and would arrange the environment to make it viable for themselves (Lenton and Dutreuil, 2020). This viability would first be achieved not by competition but by coordination between species and kingdoms, or even by symbiosis, as Margulis (1993; 1998) suggested. What produces the biogeochemical processes that determine the climatic composition and materials of the Earth is therefore sets of living organisms that 'hold together'.

In Dutreuil's thesis (2016), we learn more about the story of the experiment leading to the theory. After assembling a collection of algae, Lovelock analysed, with a chromatograph in gaseous phase, a particular chemical compound in the alga (DMS, dimethyl sulphide), and showed that major chemical and climatic cycles in the atmosphere were related to this compound but the scientist didn't know why there was this relation between algae and big cycles. Margulis gave him the key to the enigma by analysing the bacteria contained in the algae and showing that these chemical cycles came from it: global cycles are generated by tiny life forms. Together, they contributed to shifting the anthropocentric view of life on earth by showing the crucial role of bacteria in the production of oxygen, a viable condition for all other life forms. Lovelock showed later, with the model called "Daisyworld" that life regulates the environment, controlling through environmental feedback loops the conditions that allow it to keep itself alive. This is the same mechanism that was made by bacteria to produce oxygen in the atmosphere because they needed it, when its composition was quite different[13]. Even more surprising is the maintenance of a stable oxygen level in the atmosphere for millions of years[14]. Therefore, the level of oxygen is maintained somehow. Gaia theory suggests that the system is maintained by life itself. Life doesn't take a natural resource out there, independent from it, but life produces inside itself its own habitat. This characteristic makes it different from the concept of biosphere which appears more like a container for living beings than a direct product of them.

However, despite these troubling physiological aspects of Gaia, it would

13 Dutreuil thesis extract (translated by the author): "Oxygen is a powerful oxidant and therefore a metabolic poison, because reactive oxygen derivatives can damage cellular structures. All biological species that tolerate oxygen today have complex enzymatic devices entirely dedicated to the management of reactive oxygen derivatives. The appearance of oxygen photosynthesis thus raises an interesting evolutionary problem: before the appearance of oxygen photosynthesis there was no oxygen and therefore no oxidant powerful enough present on the Earth's surface to induce evolutionary pressures favouring the emergence of enzymes to tolerate oxygen; but the first cells practicing oxygen photosynthesis must themselves have already been equipped with such enzymes. The oxygenation of the atmosphere has therefore probably contributed to the destruction of a significant part of the biosphere present, composed mainly of anaerobic species that do not tolerate oxygen."

14 "No fire, whether forest or paper, can occur when pO2 is less than 15%. The continuous presence of coal in the sediments over the past 425 million years therefore makes it possible to first infer that pO2 has never fallen below this value. Second, the continuous presence of forests since the appearance of terrestrial plants about 370 Ma ago suggests that pO2 has never exceeded a value above a threshold above which forests would spontaneously burn" (Lovelock, 1995: 124-125)

be deeply wrong to confuse it with a large organism or a providential totality (Latour, 2017b), a confusion however widely spread, because of the confusion over the distinction between biotic and abiotic material, and more broadly because we consider the environment as something 'out there', exterior to Life:

> "We have become accustomed to considering the atmosphere, oceans, soils, and rocks as "environment," "abiotic," "physico-chemical," "external conditions," "geological." By telling us that these elements are living, Lovelock does not tell us that they function as living beings, but that they are part of all those beings that we usually recognize as living and whose material boundaries we have become accustomed to stopping at their membranes and epidermis, because we have not paid enough attention to what these living beings do and what they depend on. It is because the activities of the beings we classically recognize as living overflow and exceed what we classically recognize as the inanimate world that we must, precisely, revise the idea that this world is inanimate". (Dutreuil, 2020).

Margulis reminds us that "Gaia is not an organism. Any organism must either eat or, by photosynthesis or chemosynthesis, produce its own food. All organisms produce waste" (1998:148). Thus, no organism produces its own waste, but it is another organism's food. "Gaia itself is not an organism directly selected among many. It is an emergent property of interaction among organisms, the spherical planet on which they reside, and an energy source, the sun" (1998:149). According to bacteriologists, the organism centred view could be an ecologist's peculiarity who sees organism as an individual in an environment. A vision that bacteriologists do not share because they must see masses of a population to be able to discern bacterial behaviour, a bacterium being too microscopic to be isolated. Bacteriologists therefore do not dissociate complex association of livings to their environment, as they literally form environment. Margulis reminds us that not only do bacteria rule the world, they are also the fabric of life on Earth[15], and they modify the chemistry of the Earth for their own benefits.

15 See the film on Lynn Margulis, *Symbiotic Earth*, by John Feldman

Instead of an organism, Volk proposes a conception of Gaia as a major metabolic waste disposal: “The biosphere is a co-evolved entity composed of life and what are essentially products derived from life and the effects of these products (...). It is a vast world of waste (one big waste-world). (...) With regard to CO_2 in the atmosphere, more than 99% of the total reservoir has recently been released by a living being breathing rather than by a volcano. For nitrogen, more than 99% was released by living denitrifiers rather than volcanoes. And for methane and other trace gases, more than 99% was released by living prokaryotes rather than volcanoes. The atmosphere is a gigantic garbage dump” (Volk, 2004:31-32). According to Dutreuil, Gaia would have marked a renewal of the ontology of sciences of nature by offering a new object to Earth sciences and an alternative to the concept of Nature. More importantly, Gaia would have been developed at the beginning of studies on pollution. Lovelock, as a scientist working as a consultant for energetic enterprises (such as Total), would have elaborated his Gaia theory to explain the role of anthropogenic pollutants in an Earth taken as a system, reactive to chemical inputs. Gaia would be therefore a framework to think global pollution, and a precursor at the concept of Anthropocene. As a result, Dutreuil concludes that Gaia contributes to naturalise the concept of pollution. It can be reversed: Gaia is a “pollutionisation” of the concept of nature (defining nature through the pollution), contributing to challenge entirely “nature”. Margulis confirms this hypothesis: “The oxygen we need to breathe began as a toxin; it still is.(…) Pollution is natural. ‘Waste not’ is an exhortation, not a description” (Margulis, 1998:151). As a result, a population collapses because nothing can eat or breathe its own waste. This means that the Anthropocene is the result of human shortcoming: the production of waste that cannot be cycled in Gaia.

As a consequence, the traditional distinction between nature and the artificial world no longer allows us to understand ecology. Instead, firstly we should see the entire Earth as a polluted environment, where viability depends on the limit of recyclability. Secondly, we should not separate the action of bacteria (and others) from human impact but study them at the same time. Gaia, focusing on human and non-human multi-dimensional entanglements blur the lines between the natural and artificial world and contributes to shake sciences, but also as we will see, the Humanities.

2.3 The Anthropocene & Gaia in Humanities

Originating from the sciences and explaining environmental changes, both terms, the 'Anthropocene' and 'Gaia', were quickly embraced by environmental humanities, with a preference for the Anthropocene, because of its straightforwardness, over Gaia.

The Anthropocene spreads among the Humanities, especially in social sciences, anthropology, as it put into question the place and the role of humans on Earth. From the Anthropocene, many different names have been given to this period, each one emphasising what researchers consider to be the main cause of the dramatic disruption of society and the environment in which we currently live: Capitalocene, Plantationocene, Technopocene (See the list of names compiled by Hallé & Milon, 2020). Some Anthropocene schools have even emerged in Europe (Lussault, Lyon "Ecole de l'Anthropocène"[16], Berlin HKW[17]).

Two key references are crucial for understanding the scope of the Anthropocene, one giving a historical perspective and the other a geological one, *The Shock of the Anthropocene* (Bonneuil and Fressoz 2016) and *Atlas de l'Anthropocène* (Gemmene and Rankovic 2019). In a historical perspective, Bonneuil and Fressoz recount the emergence of this exponential growth in human history[18], since the 16th century with explorations. For them, 1945 is also a compelling date for the Anthropocene as it is the first nuclear bomb. There is also the great acceleration in the 1980s. The Anthropocene is then much more a trajectory, a development, that a point marker when humanity would have tipped. From a more geopolitical perspective, Gemmene and Rankovic present a complete and documented panorama of the effects of the Anthropocene in an encyclopaedic form with maps and graphs that give a snapshot of the period, mixing geography, science and humanities, addressing both social issues (migration,

16 https://ecoleanthropocene.universite-lyon.fr/une-universite-ouverte-mondiale-sur-le-changement-global-196219.kjsp?RH=1573205532900&RF=1606461002446

17 https://www.hkw.de/en/programm/themen/das_anthropozaen_am_hkw/das_anthropozaen_am_hkw_start.php

18 The authors account for a human history highlighted by Anthropocene era. They show how the exploitation of resources by the capitalist system is at the origin of the Anthropocene as defined by Earth scientists.

poverty, etc.) and environmental issues (extension of species, rising water levels, etc.). The planet has taken a new trajectory, the main cause of which was the actions that humanity had undertaken to modify the planet, first to satisfy vital needs such as living and eating, then to increase their potential exponentially: to develop, progress, consume, grow, rise.

However, the term Anthropocene raises questions regarding the name given to this epoch of massive environmental disturbances and lead to tremendous disputes in social sciences: what is the Anthropos in the Anthropocene? Many social scholars argue that the reference to a universal Anthropos tends to erase the complexity of the crisis and increases inequalities (Haraway et al., 2016; Danowski and De Castro, 2014). Not all humans are responsible for the over-consumption that leads to climate change: rather some are the victims. Moreover, the emphasis on the human as a global force, dissipating energy on unprecedented scales, risks fostering the emergence of geo-engineering solutions as already advocated by the proponents of the "Good Anthropocene" (Breakthrough Institute[19]) and, consequently, leading to the same social inequalities. Aware of this reality, some researchers nevertheless consider the Anthropocene to be a stimulating notion, particularly in terms of detecting our allies and enemies (Latour, 2018; Research Action "Où Atterrir? 2018-2021[20]), or as a term that disrupts fields and methodologies (AURA: Aarhus University Research on the Anthropocene in Danemark, with social scholars, Tsing, Bubandt, Funch, Svenning, Swanson, Degen, and many more[21]), fostering new and often interdisciplinary lines of research.

The Anthropocene affects the individual understanding of time and brings disorientation, sometimes desperation (Stengers, 2015). The Anthropocene deploys a wide range of time scales that are impossible for the human mind to grasp, from the microsecond to a million years, destabilising our present (Chakrabarty, 2009). Indeed, carbon dioxide is rapidly released in the air, whereas it takes millions of years for the carbonate that constitutes fossil fuel to be produced by the accumulation of layers

19 https://thebreakthrough.org/articles/can-we-have-a-good-anthropocene
20 Projet research action funded by French Ministry of the Environment, *Où Atterrir* ? Bruno Latour, S-Composiiton, SOC (Société d'Objets Cartographiques), 2019-2021. Workshops, conferences, cartographies, scenography. Limousin Region with 50 participants, France.
21 https://anthropocene.au.dk

made up of billions of dead micro-creatures (Zalasiewicz, 2016a). Similarly, the hazard of radioactive explosion crosses borders in seconds, while the components of radioactive atoms whose nuclei have been separated produce waste that will last for centuries in the strata in which humans try to hide them, to prevent their discovery by future generations (Moss and Galison, 2015; Madsen, 2010). How can we account for both rapid transformations and much longer ones? How can we show that our traditional regular chronology based on a line of progress is completely disrupted now, looking more like a spiral than a straight line (Bensaude-Vincent, 2021)?

Not only are times and epochs difficult to understand, but also the spatial distribution of territories (Latour, 2017a). The relationships between space and time, local and global, were stable notions that the Anthropocene now destabilises. Indeed, entities are rapidly degrading: forests, fossils, nutrients, in places that we considered unspoiled by man. On the contrary, what we thought we could get easily, quickly and as an inexhaustible supply, that is resources close to our habitat, such as water, soil or fresh air, take much longer to renew themselves and are often dragged from far away. This effect results from the disconnection between the territory of life and the territory of subsistence, as we will see later. As Vivieros de Castro puts it: "The steadily growing scarcity of time (acceleration) and space (contraction) is transforming these conditioning forms of our sensibility (Kant 1999 [1787]) into damaged frames conditioned by our insensitiveness" (2019). In addition, all these disturbed temporalities are variable depending on the location. It is impossible to have the same effects in two different places.

The Anthropocene, while challenging the separation of man and nature, does not fundamentally challenge the notions of nature and human: what is nature, what is human? Nor does it succeed in building perspectives for the future by addressing the question of habitability. Gaia is a more radical ecological concept that proposes a new definition of life on Earth. For most researchers in the humanities and social sciences, it provides an alternative to 'nature'.

Yet few academics venture to deal with Gaia. Stengers and Latour have contributed to spread the idea of Gaia as an alternative to Nature (Stengers with "the revenge of Gaia", 2015, and Latour with "facing

Gaia", 2017a). Recently, two collective publications assemble articles from various scholars discussing this idea: the ZKM *Critical Zones* exhibition catalogue edited by Latour & Weibel (2020), and *Le cri de Gaia*, edited by Ait Touati & Coccia (2021). Their understanding of Gaia is not different from Latour and Stengers but expands it to other fields (theatre, theology, anthropology, art, etc), so that we will mainly refer to the origins of Gaia in the humanities as introduced by the main references.

The philosopher Stengers (2015) was the first to use Gaia to move away from the idea of ancient Nature and its regime of human-non-human relations based on resource exploitation, extraction and privatization. Stengers takes us out of the anthropocentric perspective and defines a cosmopolitical one. Gaia is the other 'nature' that is not a docile background to our actions, but a much more frightening nature, that Stengers proposes to name, after Lovelock and Margulis, Gaia, to echo both the scientific hypothesis but also a mythological presence that would require us to rethink our cosmology. Thus, Gaia "intrudes into a story that the descendants of the industrial revolution had told as that of human emancipation freeing itself from the constraints of nature." (Stengers, 2014:148). Stengers argues here that we have to reorganise ourselves in the complex world made up by beings of a vindictive nature, from which we thought we had extracted ourselves but that we had never really left. Drawing inspiration from Latour and Stengers, Viveiros de Castro (2019) defines Gaia as the "always unstable coexistence of different modes of existence", which leads, according to him, to an "ontological anarchism", that is the need to remain open to all voices because we may not all have the same framework of thought to understand them. Thus, the question may not be that of the Anthropocene - taken as a global phenomenon; indeed, what question can be asked to the Anthropocene? Who will answer for/of it? The question of whether or not the planet is habitable can only be asked to entities, to beings capable of answers[22], to chains of beings capable of organising themselves and transforming the Earth in one way or another[23]. This requires a re-evaluation of the way we observe and ask questions to the living studied, from a point

22 According to the Stengers and Despret method, you have to ask the right questions, to the right beings, if you want to have an adequate answer.
23 In positive or negative feedback loops, as studied by cybernetics.

of view that does not place us anywhere else but among them. Sharing territories with them, learning the interactions that multiply the domains of friction and move Gaia, requires, according to Stengers, to reposition oneself towards beings whose situation we also seek to know: "It is a question of abandoning what 'calmed us down' (...), not for a new representation but to learn to ask a question whose answer belongs to the being it interests, and which requires the person who asks it to learn to hear the answer given to it"[24] (2014:158). The task is therefore to ask questions to the living, and to equip oneself with the means to accept their answers. Indeed, ecology should not be reduced to a question addressed from organisms to organisms but would rather be an entanglement of interdependent processes.

Gaia shifts the Anthropocene from an anthropocentric view to a cosmopolitical view. While Anthropocene places man at the centre of the planet and does not deal with the description of relationships with non-humans, Gaia helps to counterbalance this, not by mitigating its impact but by placing it in the complexity of terrestrial relationships as suggested by Stengers (2013, 2015). As the place of humans in Gaia is not discussed in the scientific Gaia hypothesis, this debate is still open (Lenton and Latour, 2018). Moreover, as there is not an environment on one hand and organisms on the other, the notion of how the world is constituted is radically put into question: "there is not an environment on one side of the organisms and on the other, but an overlapping of mutual arrangements" (Latour, 2018:98). Latour and Lenton, associating humanities and earth sciences, venture to deploy some aspects of what a political program seriously considering the revolution introduced by Gaia would be like. In their joint article (2019), "Extending the domain of freedom, or why Gaia is so hard to understand", they argue that entities, having agentivity and reflexivity on their actions through feedback loops, are consequently *free* and not determined by natural laws nor human laws. As they put: "the novelty introduced in the notion of Earth by the joint efforts of Lovelock and Margulis consists in granting *historicity and agency to all life forms*, that is, in attributing to the life forms them-

24 Translated from French :« Il s'agit d'abandonner ce qui nous « tranquillisait » (…), et cela non pour une nouvelle représentation mais pour apprendre à poser une question dont la réponse appartient à l'être qu'elle intéresse, et qui requiert de celle ou celui qui la pose apprenne à entendre la réponse qui lui est apportée. »

selves the task of creating the conditions for lasting in time and expanding in space. It is in that sense that they can be said to obey their own laws" (Latour and Lenton 2019:664). They suggest a new understanding of what freedom means, extracted from natural laws that no longer exist. Conversely, we can no longer rely on natural laws because they are a false framework.

Gaia thus redefines the materiality of territories by arguing that any product, any physical portion of territory is the result of living beings. Let us subtract the living, we would have no landscape, no habitable conditions on Earth: "Lovelock compares the chemistry of the Earth's atmosphere to a sandcastle found on a beach, or a bird's nest. They, too, are obviously products of life" (Margulis, 1998:154). In an article discussing *Facing Gaia*, Coccia (2019) suggests overcoming the distinction between soils and subjects, to apprehend them jointly, ontologically inseparable. If space is equal to agents, then territory and subjects, individuals or entities are merged. To live/to be in/a territory would be, as he puts, to "make everyone the living space of the highest number of other actors - living and non-living" (2019:42)[25]. Thus, Gaia sets the scene for a more cosmopolitical understanding of the Earth: politics of the earth that would attempt to multiply the opportunities for relationships that would make it possible for many beings to co-exist.

Among these various paths to understand the New Climatic Regime in sciences or humanities, what are the positions of the field of design? How does the field account for these disorientations in space and time? The specificity of design, whether architectural, urban, or landscape, can be indeed defined as the reflection on space, whether by its conceptualisation (what is space?) or its actual realisation (how to arrange elements, programmatic or material, on a given site?). Thus, is there a new understanding of space emerging from the Anthropocene and/or Gaia?

The main proposition to tackle the scale of the Anthropocene is to rethink architecture through geological times, since the Anthropocene comes first from the discovery of anomalies in the study of rocks, as developed in two precursors collective digital books *Architecture in the Anthropocene*

25 Translated for French: « Il s'agira de transformer tout dans la Terre des autres, de faire de chacun le terrain de vie du nombre le plus élevé d'autres acteurs – vivants et non vivants. »

(Turpin, 2013) and *Making the Geologic Now* (Ellsworth and Kruse, 2013). Geomorphology is indeed not at the heart of the designers' practice, nor is the use of geological maps to understand on which rocks a project is based, which mostly refer to geography. With geology however, architects become aware of the materiality of the rocks because they are increasingly altered by human products, including future technofossils[26] from building constructions. Geology brings a long-time scale to architectural thinking, as the architects Design Earth show with their graphic speculative narratives around 'geostories' (Design Earth, 2018). Similarly, the book *Provisional Cities* (Tyszczuk, 2018) is dedicated to the Anthropocene issue in Architecture and City studies. Renata Tyszczuk (2016, 2018), scholar in Architecture, introduces the term "non-conformities" drawing on geologists such as Zalasiewicz. Non-conformities are the materialization of events onto rocks, their imprints, by which geologists evaluate different temporalities. There are schisms, clashes, i.e. past, sudden or longer glaciations, past climatic events. According to Tyszczuk, non-conformities are a good way of thinking the Anthropocene. Thus, most architectural scholars deal with the Anthropocene from the perspective of this reconciliation of human time with geological time.

Other authors also point out that the attention of soils, in pedology, have also been erased from official documents describing the territories for a very long time (Denizen, 2013). It is only recently that urban soils have been included on maps. Previously, a white (white-grey area) was left on maps. As a result, urbanists have not paid much attention to soil in planning. With the problematic lack of fertile soil which has been eroded or excavated by overexploitation, the soils become visible again. Paradoxically, the soil is eventually scrutinized while it is dying.

All these authors call for new narratives to the habitability of the Earth and architecture. In her 'cautionary tales', Tyszczuk suggests relying on various territories of investigation to understand the Anthropocene. She claims that such territories have been somehow underestimated by the discipline. She also brings to the field of architecture a highlighted summary of the trajectory of Anthropocene through earth sciences and social sciences since

26 Zalasiewicz names technofossils the materials that human has created and that are now found in all stratigraphic layers, sometimes at depth. Technofossils are made of concrete, aluminum, plastics.

its appearance, with authors that we have discussed previously. These literatures attempt at grasping the scope of the Anthropocene and making sense of it by gathering contributions from different disciplines and putting them in conversation with architecture or landscape design. The many authors discussing the topic assess that the Anthropocene requires a change in our understanding of nature and the place of humans in it (Grosz, 2013).

This overview shows that the Anthropocene has spread to different academic fields, including design, but still at its margin. However, there is no literature on the consequences of Gaia theory on design. Perhaps because Gaia comes from a science that architects are less familiar with (chemistry), and a science that has no 'visual' compared to geology. As the concept of Gaia is less known in architectural discourse, we can therefore identify here an important gap in our field, especially since, as we have seen, the question posed by Gaia is that of the world's habitability. This perspective can provide new avenues of research, which we will explore in this thesis.

The Anthropocene raises debates within the sciences, the humanities and design about the term itself, or about how to approach it. Some researchers criticize it, others refer to it, and still others seek new paths. Originally a scientific term, it is now widely discussed in the social sciences and increasingly in design. As for Gaia, also of scientific origin, it is less widespread in the human sciences and there are no references in design.

What emerges from these discussions about the Anthropocene is a critique of an anthropocentric view, i.e. one that places humans, whoever they may be, at the centre of the world, without taking into account all the connections and the existence of other creatures, other living beings. This view is multifaceted and permeates our daily understanding of the world. On the other hand, some researchers develop an alternative view drawing on scientific facts: this is the cosmopolitical view, which develops the idea that humans are not alone in shaping the world and that a different cosmology is needed to confront the Anthropocene. This view is in fact close to the Gaia hypothesis. We will develop what this view entails and how it does or does not materialise in design theory. This will reveal some gaps that this dissertation aims to address.

2.4 The Anthropocentric View

In this part, we will examine how the anthropocentric view permeates thinking and practice at different levels: from cosmology (the way a community relates to other non-human entities), to economic and landscape management issues, to design practices and visualisations of the earth. The first task is to understand what idea of nature underlies the anthropocentric view. The second task is to examine how landscapes are shaped by this vision and what sustains their existence. In this way, we seek to understand how design contributes to the perpetuation of these anthropocentric landscapes. Finally, we will examine which views, which visuals, which representations of the world sustain and disseminate this view.

From an anthropocentric perspective, nature, seen as a single entity, is conceived as a separate and different entity from the human world. We are in the traditional Western regime of understanding nature, which Descola calls ‘naturalism’ (Descola, 2005; 2016) and which separates nature from culture. In this tradition, the human body is placed at the centre of the world and other creatures revolve around it. Gradually, however, man is placed outside, above, on the same level as the omniscient eye of God, so that the human eye oversees the world, which is created, and which can be remodelled for and by man himself.

This anthropocentric view considers matter as inanimate before entering the human world. According to Picon’s history study, architecture is ‘the animation of matter’, close to art sculpture (Picon 2018). This implies that matter has no agentivity until it has passed through human hands, until it is moulded by its second creator. From an anthropocentric perspective, architecture is the creator’s will on materials that resist him. Since matter, nature and the environment are ‘out there’, i. e. dissociated from the civilized world conceived by human architects, they can be measured by perspective, and mapped from a top-down view – which are actually the same conceptual tool, as Farinelli (2009), a historian and geographer points out. Therefore, man being at the centre of a space, his point of view arranges things in front of him. Latour, in Politics of Nature (2004a), shows how this affects our politics. This approach to the world indeed removes natural entities from daily human politics, as they are mute and without capacity of acting, of playing a role in the environment where humans evolve. Matter is seen as something de-animated that must be animated by a creator. But what if the matter is already alive, already animated and generated by a living being? Latour (2017a) argues that our modern world and the entities, living or non-living (rocks) that compose it, have been de-animated so that we can take them as resources that can be extracted and exploited. De-animation means that the 'thing' is extracted from its network of relationships: its environment, and the whole network of other beings that allow it to maintain itself in its existence, that is, its territory of subsistence.

In the 17th century, the concept of landscape emerged, regrouping the natural entities into a single notion. Olwig (1996; 2002; 2008) and Aït-Touati (2020) point out that the notion of landscape, which comes from the arts of setting (décor in theatre), conveys the idea of a background, a beautiful setting to support and enhance an action performed by humans. Theatre arts and garden arts were indeed very close in the 17th century (Olwig 2011). From then on, most of parks and gardens landscaping today still aims at creating beautiful views, panoramas, so that humans can enjoy pleasant walks. With the industrialisation of landscapes, this small-scale landscaping became larger: the planning on a territorial scale is based on the idea that the environment is a background for human activities.

Landscape management is now largely based on an anthropocentric perspective which has dramatic consequences on the ecologies of a land. Tsing argues that the spread of the Anthropocene is directly linked to industrial planting processes that allow industries to export and expand indigenous and small-scale crops in huge mono-specific plantations. She calls it the Plantationocene (Haraway, 2015; Tsing, 2015; Haraway et al., 2016; Haraway and Tsing, 2019). Manufacturers simply reproduce the same process but at a larger scale. This is what she calls "scalability": the absence of adaptive production processes according to the size and particularity of a territory. The industrial process extends the system without changing the components. Scalability is used in techniques and business to change scale without changing relationships[27]. The elements just undergo a homothety. It is interesting to note that this process is also a well-known design software drawing tool in Architecture and Planning. The problem is that when something goes wrong, for example when a parasite enters a culture, it can thrive, destroying a large part of a landscape and thus ruining an entire territory that previously fed local populations (humans and non-humans). Simplifying complex ecology is at the heart of the process in order to control plant growth. However, mastery of life is a rather utopian ideology. When pests and pathogens spread, landscapes become wild or out of control again, i.e. "feral" (Tsing et al., *Feral Atlas,* 2021[28]). Ecological theory has given the name "landscape formations" to the patches that are distinguished from one other by the type of beings and phenomena involved in an alliance that will cause perturbations leading to either destruction or improvement of the environmental conditions. This is what Tsing (2017a, 2018) interprets as "Holocene resurgences", in contrast to the "Anthropocene proliferation" patches of the anthropocentric landscapes.

Not only are the "Anthropocene proliferation" landscapes unsustainable, but there are also enslaved territories for sustaining other countries. Pomeranz (2000) argues that after 1750 European countries, being aware that their soil was eroding much faster than it could be regenerated by labour-intensive care, started to search for other lands to cultivate. America provided the land intensive products that relieved pressure on the land in Britain and this then allowed industry to take over the economy. Thus,

27 "Progress itself has often been defined by its ability to make projects expand without changing their framing assumptions. This quality is "scalability." The term is a bit confusing, because it could be interpreted to mean "able to be discussed in terms of scale." Both scalable and nonscalable projects, however, can be discussed in relation to scale. Scalability, in contrast, is the ability of a project to change scales smoothly without any change in project frames. A scalable business, for example, does not change its organization as it expands. This is possible only if business relations are not transformative, changing the business as new relations are added. Similarly, a scalable research project admits only data that already fit the research frame. Scalability requires that project elements be oblivious to indeterminacies of encounter; that's how they allow smooth expansion. Thus, too, scalability banishes meaningful diversity, that is, diversity that might change things." Tsing, *The Mushroom at the End of the World*, page 38

28 « *Feral Atlas* invites you to explore the ecological worlds created when nonhuman entities become tangled up with human infrastructure projects. Seventy-nine field reports from scientists, humanists, and artists show you how to recognize "feral" ecologies, that is, ecologies that have been encouraged by human-built infrastructures, but which have developed and spread beyond human control. These infrastructural effects, *Feral Atlas* argues, are the Anthropocene. » Website introduction to the Feral Atlas. https://feralatlas.org.

to counter the effects of degradation States have decided to expand their lands elsewhere, i.e. in colonies, giving their people the feeling of having access to infinite resources. These are called 'phantom/ghost acreages': the sum of the seized overseas lands necessary for the survival of those living on degraded ground. A territory, understood as what makes it possible for a people to survive on its own ground, is therefore not limited to the borders of sovereign States, to that ground on which we think we live. This process has led to a total disconnection between a land where law and freedom are guaranteed and another land for which no one feels any responsibility even though they are dependent upon it (see chapter "Disconnected" in Latour and Weibel, 2020). It is clear that in addition to the legal territory there is a real, often distant material territory, a ghost territory for those who profit from the sources of wealth located there. Developing Latour's ideas (2018), Charbonnier (2020; 2021) argues that national borders do not serve to bound the territory within which we think we live. Instead territory is here understood as what allows one to survive. Very concretely these are the beings and things, many of which derive from elsewhere, that allow one to keep oneself alive. Quite simply, we depend on them. Focusing on this notion of territory instead of landscape is interesting because it relocates the problem into a broader socio-economic context.

Nowadays, this idea of infinite spatial expansion and thus infinite resources is challenged by the Anthropocene. Presented as an alternative, the notion of ecosystem services argues that we can infer the economic value of the services that nature provides us (value of biodiversity, of trees in a city, etc) as a key part of a rationale to protect it. It defines the value of an ecosystem through the qualities and quantities that an ecosystem provides to humans. Thus, the 'good' natural processes are those that serve humans best; they are the processes will be conserved. But as Donna Haraway points out: "It promised to break down nature and culture, but at the cost of turning everything into circuits of monetarization and accounting" (Haraway et al., 2016:539): these types of management barely hide the memory of the colonization and slavery that underlie them. For lack of a better solution, however, they are widely used now in urban and landscape design.

To counteract the destructive planning methods used by modernity to develop cities despite the vernacular understanding of the territories, landscape is now at the heart of projects addressing environmental issues. Pressure is thus being put on landscape architects: how to build on agricultural land while conserving nature? How can nature be integrated into dense urban environments in order to cool neighbourhoods that burn under increasingly high temperatures in summer? How can abandoned, post-industrial, commercial sites or simply the banks of rivers or former railways be reclaimed through a renaturing project? Understanding such issues is becoming increasingly crucial: the fertile land on which to grow a landscape project is increasingly difficult to find[29].

The trend of bioregionalism (Berg, 1977; Berg and Mills, 1981; Rollot and Schaffner, 2021), or genius loci (Norberg-Schulz, 1997), is supposed to offer a guide to designers seeking to be more attentive to the site. But this approach was already at the heart of landscape design when this field emerged. *Design with Nature* (MacHarg, 1969) is indeed one of the first books for practitioners to introduce methods for design with nature. One is to merge the model of nature with the model of development. Urban space would have to follow the forms and patterns offered by existing open spaces. The objective is to provide better settlements for humans, thus classifying land with a value system according to natural processes and their suitability for urban development, often understood as mutually complementary. As "urban growth tends to be incremental and unrelated to natural processes on the site" (MacHarg, 1969:65), MacHarg's method planning proposes a land management manual based on simple and common-sense prescriptions (water supply and conservation, soil fertility maintenance for agriculture, forest health maintenance, etc.).

Following his method but still facing the same difficulties, all landscape projects provide such manuals to public managers and clients of land studies. By paying attention to nature's patterns, landscape designers argue that natural processes can absorb urban development. To do this, physiographic guidelines should be applied on site. This may involve choosing

29 There is an increase of 200 % of the cost of fertile soil these last 5 years in Europe. Source Baseland paysagistes

the right location for settlements, conserving and saving existing resources, choosing the right orientation (to sun, wind, etc.), i.e. taking into consideration all the regional values with which the city can be developed. With regard to the method, they proceed in layers, dividing territorial characteristics into cultural or natural values. This method is still used, augmented by the GIS computer tool that displays the same layers. Then, the programming of the land results from the superposition and analysis of these layers, defining areas for urbanization, others for recreation, and still others for agriculture, roads, afforestation, etc. With minor updates this design process persists in landscape practices. Layer decomposition makes it possible to extract natural values analytically according to the usefulness they can bring to humans.

However, does this approach really allow us to move beyond the cosmology of the anthropocentric view, and to re-qualify our relationship with nature? This design approach is indeed based on the assumption that species, including humans, integrate into their environment. Consequently, design would be the technique by which we could make the environment better suited and fitter for us (MacHarg, 1969)[30]. These are the basics of good practices seeking to adapt cities to the natural environment: finding the best design according to a site that is known—and will continue to be known because the same characteristics will last for centuries. However, with the Anthropocene none of these tactics are now sufficient since those characteristics of environment that were supposedly stable are in fact changing, and very quickly. What if the status of nature is changing from simple passive background to main actor of the scene? How then to clarify and elicit its complexity?

In *Facing Gaia*, Latour (2017a) argues that we do not have a realistic view of the Earth that could help us understand the network of our attachments to living beings. Indeed, if we look at the Earth from space, it is impossible to imagine that the result has been shaped by living entities. One of the problems that prevents us from understanding the complexity of nature is

30 “The environment – land, sea, air, and creatures – does change; and so the question arises, can the environment be changed intentionally to make more fit, to make it more fitting for man and the other creatures of the world? Yes, but to do this one must know the environment, its creatures and their interactions – which is to say ecology. This is the essential precondition for planning – the formulation of choices related to goals and the means for their realisation.” p52

that we have limited representations of territories, landscapes and the Earth.

The image used to depict the Anthropocene is a view of the Earth arranged so that its entirety can be grasped by human view in a second. This is the so-called blue marble inherited from cybernetics sciences[31]. This image is composed now by thousands of photographs taken from space by satellites. Its construction allows a homogenisation of the Earth's places. First intended for military use, satellite images have become accessible to the public via the Internet. These space-based surveys were developed during the Cold War, particularly in the Arctic to monitor the passage of ships between the US and the USSR. This highly monitored strategic territory generated a wealth of data that has since been recovered by climate scientists and used to track the evolution of snowmelt (Grevsmühl, 2014; 2016). With cybernetics, the Earth is seeing itself, as reflected in feedback loops. For the proponents of cybernetics, this awareness is maintained by constant monitoring. Cybernetics has returned to us the image of the Earth as a globe. Information is provided to everyone by this obsessive monitoring and, together with the awareness that we manage a territory that we are observing, a certain idea of the world is stabilized. Lands are shaped by well-defined boundaries and borders (*partes extra partes*) thanks to more and more efficient survey tools that enable the complete division and fragmentation of the Earth: its parts cut by lines that assign human property rights to the soil, but also to the air above and the ground below[32]. In this new way of grasping the world, maps are essentially tools for collecting and disseminating data. Historically, their structure was designed to enable the making of changes after the return from travels, mainly to rectify the roads, since the political leadership was clearly oriented towards the discovery and colonisation of new lands. The map has thus become an instrument of conquest for military or navigational purposes (Brotton, 2013) [33]. Built with mathematics, their objective is now clear and fixed once and for all: to make the terrain as realistic as possible (topographic maps), and to define the boundaries of the territories.

31 The first full image of the "blue planet" is taken by the Apollo 17 space mission in December 1972.

32 Legal principle of *Cuius est solum, ejus est usque ad caelum et ad inferos*

33 For Jeremy Brotton, who wrote the *History of the world in twelve maps*, cartographic visualisations are not simple representation of a world standing out there: they literally make the world as it is.

These anthropocentric maps flatten moving entities and living beings in the Euclidean grid that assigns them a locked position and controls them. For historians of science Daston and Galison (2007), the 18th century marked a turning point in the way nature was analysed by science. Drawing on Whitehead's natural philosophy, Debaise (2017) has studied what Whitehead called the bifurcation of nature. Modern science distinguishes between characteristics of nature those that are important and will therefore be the subject of scientific study and those that are not interesting to work on. In this process, space has become the most important element for describing nature in terms of simple localisation: where is the object located as a fixed point in a time interval? As a result, it was no longer important to take into account intensity, events and flows that make up nature. However, these aerial views are criticized by Nagel (1986) who calls them "views from nowhere", that is, views that don't situate themselves and thus are ambivalent. Our relationship to the world is controlled by triangulation, a geometric process that is built from an external, celestial, abstract point (Kurgan, 2013). Even if maps have always oscillated between interpretations inherited from ancient cosmologies where the Earth is traversed by dynamics, folded and moving, objectifying field records attempt to freeze these interpretations in order to produce a 'final' and 'finished' image of the Earth. Therein lies the problem: in the daily practice of a planner, an architect, or an urbanist or landscaper, the basic tool is now Google Earth. Yet no one lives in this space. According to Farinelli's criticisms (2009), this tool has transformed the Earth into modern territory and has allowed the development of photomaps, omnipresent today in our lives and design tools. Olwig (2008) develops a similar critique in landscape research, analysing more precisely the correspondence between territorial policies and the spatial tools available to delimit a territory, i.e. the Euclidean grid with which any mapping is produced. Both make explicit how the map is the spatial translation of the political law - the *nomos* (first measure, first law, from which all other measurement criteria originate), the political law being intrinsically geometric in nature. The deed of ownership locks up a piece of land, constituting the so-called enclosures which, from the 18th century onwards, extended to the whole planet. In Euclidian geometry the line has no width, the dot has no depth; there is no space for the living. What matters are only the distances between things, flattened for a fixed and motionless subject that measures the Earth by relying on abstract geometrical lines, the latitudes and longitudes that run around the planet. Continuity (no interruption), homogeneity (identity of the material) and isotropism (regularity of the parts in relation to the direction) are the properties that define the space and the map. This space is a standard defined by linear metric intervals. In the anthropocentric view, Earth lost materiality and exhibited a weakened universality, that resulted in a homogeneous point of view that flattens all other worlds. If we wanted to shift the anthropocentric view, then the maps should be rethought to convey this conception of territory: "not as a two-dimensional map segment, but as what we depend on to survive, what we are able to explain or visualise, what we are ready to defend." (Latour, 2017a: 338-339). In this way, the territories overlap, but since we do not have this type of visualisation of complexity, we still base the management of landscapes on an idea of simplification. Many practitioners, artists or architects, criticise the anthropocentric view in experimental works on aerial mappings. Forensic Architecture[34], Italian Limes[35], Territorial Agency[36], the Monsoon Assemblage research group[37], use these visualisations as a critique of the system to report various injustices or environmental issues. Forensic Architecture shows how chemicals spread beyond borders in the exhibition Cloud Studies[38] by retracing the particles according to the winds. Italian Limes (Ferrari et al., 2019) records the moving border at the Swiss-Italian frontier in the Alps that is changing every day because of ice melting, showing the absurdity of State borders in the face of climate change. Territorial Agency maps the hidden infrastructure that connects the lands through the ocean and seas, and how it impacts marine life without us acknowledging it[39]. The Monsoon Assemblage research group led by Lindsay Bremner

34 https://forensic-architecture.org
35 http://www.italianlimes.net
36 https://www.territorialagency.com/oceans
37 http://www.monass.org
38 The Whitworth, Manchester, United Kingdom. 02.07.2021 - 17.10.2021
Exhibition at the ZKM : https://critical-zones.zkm.de/#!/detail:cloud-studies
39 Territorial Agency: Oceans in Transformation, The Architecture of the Continental Shelf, 2019–2020. The North Atlantic continual shelf of Europe, Remote sensing data. ZKM exhibition *Critical Zones. Observatories for Earthly Politics.* https://critical-zones.zkm.de/#!/detail:oceans-in-transformation-the-architecture-of-the-continental-shelf

traces the impact of climate change on the monsoon in Asian territories and produces experimental mappings to follow the changing forms of the Earth. Through a virtual exhibition[40], the Monsoon Assemblage presents five years of research as an interplay of drawings, ethnography and conversations with many scholars and entities, geographies and materials. The drawings mostly created by John Cook (Global seasonal envelopments) capture the moving aspect of monsoon climate, between air, water and grounds.

In the anthropocentric maps, the idea of 'nature' is not put in question, as da Cunha argues in *The Invention of River* (2018): "there are things the existences of which are beyond dispute. One may appreciate or question their essence – their cultural image, the inhabitants' view of them, their appropriation 'to serve as infrastructure or background of our collective existence', their natural or cultural status – but their existence is beyond question" (2018:14). He asks then this important question and brings a new theoretical challenge: "But can the elements of landscape be taken for granted?" After all, for instance, the existence of a river as an entity as such requires an act of discernment and separation. Indeed, the object river is the result of a choice of a "moment in the hydrologic cycle to bring land and water into being" (ibid.). In landscape design, it is usual to take into account the diversity of the elements that revolve around the project. These elements, plants, paths, water, buildings, are inserted and distributed in the new projected space. However, these landscape elements are taken for granted, treated as pre-defined entities. The maps drawn following this preconception work to pre-schedule of the world in a way that is little questioned. Da Cunha further unpacks how the way we draw things on maps has contributed to the naturalization of territories, thereby producing certain idea of what a natural landscape is. According to him, a landscape is the delineation of entities captured through lines. He extensively exemplifies this argument by detailing the ways rivers are identified and visualised as such: the river is just a line drawn at the surface of the Earth to differentiate water from land. But in physical terms, rivers don't exist as such entities. Indeed, da Cunha demonstrates that the land-water division, the river, is a colonial thought, realized in order to fix an entity – water – in one state: where and when it touches the

40 http://exhibition.monass.org

land, excluding the other states of the water. But the water cycle is much more expanded, notably in the form of rain. The Ganges first means rain, but has been transformed to fit the idea of "river", something possibly to be mapped and exploited. Mathur and da Cunha (2020) suggest that instead we should see lands as wetness, more or less wet, porous to rain. European see "rivers" because the water's flow is viewed as a resource. For Indians, resource is the rain. We see here that nature is a cultural construction, blurring the lines between natural or cultural things, as already argued by Latour (2004a). Further, we see that it can be unravelled through the analysis of maps – visualisations of territories (Latour, 2013[41]). Moreover, Mathur and da Cunha show how this reconsideration of water-land division through wetness could bring a better scientific understanding of the real water processes, understanding it as it was thought of in the past. To repeat what has been said previously: conventional visualisation stabilises the river in one line, rather than seeing it as a flow. This "per usual" visualisation of nature not only defines a natural concept, but also involves geopolitical decisions. Instead of taking into account the complexity of nature, conventional visualisation reduces water to a simple limit for military and ideological purposes.

In this section, we have seen how an anthropocentric view is constructed and how the regime of visualisation gives it credibility, effectiveness and 'reality'. Thus, we can say that visualisations are important in shaping our understanding of the world and influencing our actions (design practices, landscape management, economies). We have also seen how the concept of landscape was created to convey a stable background for human activities and how it perpetuates this idea even today despite the Anthropocene.

However, some other schools of thought interpret the Anthropocene not as the ascension of Anthropos, but as the chaotic awakening of non-human entities, as in the Gaia hypothesis. From this first global

41 Chapter 4 "Learning to make room" examines the process of cartography of the Mount Aiguille: "By splitting Mont Aiguille into primary and secondary qualities, making it bifurcate into two irreconcilable modes, what is neglected is not only subjectivity, "lived experience," the "human," it is especially Mont Aiguille itself, in its own way of persisting, and, equally, the various sciences that have striven to know it and that depend on its durability to be able to deploy their chains of reference. (…) The danger is that this loss threatens to deprive us of both the map and the territory, both science and the world."

and unified approach to the Anthropocene (the anthropocentric view), we will move towards more varied attempts to give meaning to the Anthropocene: this is the cosmopolitical perspective that we will now discuss.

2.5 The Cosmopolitical View

In the cosmopolitical idea of nature, humans are part of a network of many other beings and objects. This flat ontology does not place man at the centre or outside and above the world as does the anthropocentric view. In the cosmopolitical view, nature is composed of many entities and is not seen as a single object or as a passive background. Instead, it is constituted by many actors who have their own life trajectory, a decision-making power. One of the consequences is that this view erases the separation between nature and culture, because there are objects, beings and relations that move, travel, associate through and beyond this construction. The cosmopolitical is constructed through a particular attention to composition (Latour, 2004b; 2010); it is defined by an ecology of mutually respectful practices (Stengers, 2010) or/and by multi-species entanglements if we extend the notion to the environment (Haraway, 2016). What interests us here is to understand what this cosmopolitical idea of nature brings to architecture in the Anthropocene.

Hilde Heyden examines the difference between the way social scholars and architects consider space, demonstrating an original view about this weird idea that space would be a totally passive background. She states that, traditionally, scholars in social sciences took "the existence of actual architectural and urban space as a given background, rather than as an active factor that in itself is capable of producing (such) behaviour." (2013:344). By contrast, "Like Latour and Yaneva, Thrift is serious in exploring a 'flat' ontology where humans and non-humans all take up agency and where space, rather than being 'ground' or 'background', is seen as a mediator and a connector, the materiality of which matters" (ibid.). Thus, on the one hand, space is a fixed, unchangeable surface. On the other hand, space is a depth intentionally created within which we live. Latour and Yaneva (2008) show that space is already active, in the making, in evolution, and that is the core to architecture thinking of space as the central stage rather than as a background. Moreover, space, despite being manipulable and active as a result of human activity, it is mostly its non-human constituents that give it a shape.

The cosmopolitical view thus seems more relevant for tackling the Anthropocene. The background is no longer stable: rocks, soils, tree react; indeed, all of the environment reacts to the rhythm of human time. Before the Anthropocene awareness, these elements were seen as static compared to the rapid rhythms of human activities. The Anthropocene had introduced a regime for understanding these elements differently; some change as fast as human activities. Nature is no more a silent scene detached from human actions; it is composed of entities in friction with humans, negotiating, adjusting, constantly disturbing their space. The authors advocating for the cosmopolitical view argue that we should include these entities as part of the base of our political relations. However, there is as yet no understanding of landscape that would capture this complexity.

In the following, we will focus on a particular recent approach that contributes to shifting the idea of landscape as background to a new definition of what a cosmopolitical landscape might be. We will begin by analysing the research carried out by ethnographer Anna Tsing over the last 20 years. In particular, her latest book is worth a closer look to understand cosmopolitical landscapes in the Anthropocene; with it we can ask the question: how to live in the ecological ruins of today's world?

In *The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins*, Tsing (2016) offers an ethnographic study of landscapes that is in line with her previous works on landscapes as frictions (Tsing, 2004). In her recent study, she spent six years following the network of a particular mushroom, tracing its relationships with both humans and non-humans, and describing how alternative lives are possible through its hunting and selling. The particularity of this mushroom is that it thrives on ravaged landscapes, so that new ecologies and economies emerge that are impossible to grasp by capitalist systems. Tsing's research combines geostories of geological formation, microscopic stories about the symbiosis between *Pinus* and Matsutake, as well as daily stories of those human gatherers who try to make a life for themselves between precariousness and freedom by hunting mushrooms in the forest. Matsutake, the mushroom at the other end of the world, is a rhizomatic story, as is its mode of existence. In this cosmopolitical perspective, many actors are entangled in a same life story and humans are not the main characters. Indeed, Tsing demonstrates that specificities matter and heterogeneity is the rule in landscape studies. She writes about the rhythm she has found in the forest through the art of noticing polyphonic assemblages that make worlds. Landscape is thus seen from *within* as an assemblage that can be configured and reconfigured following disturbances. To follow landscape assemblages, Tsing's methodology is based on a careful attention to more-than-humans. Using ethnographic methodology, she suggests slowing down and exploring three ways to draw an understanding of nature through the cosmopolitical view.

First, by putting our traditional beliefs into question, Tsing points out that disturbances are not always bad – because not always human, or because the landscape resulting from disturbances allows more-than-human repopulation:

"Disturbance is a change in environmental conditions that causes a pronounced change in an ecosystem. (…) Humanists, not used to thinking with disturbance, connect the term with damage. But disturbance, as used by ecologists, is not always bad and not always human. Human disturbance is not unique in its ability to stir up ecological relations. (…) Thus all landscapes are disturbed; disturbance is ordinary. But this does not limit the term. Raising the question of disturbance does not cut off discussion but opens it, allowing us to explore landscape dynamics. Whether a disturbance is bearable or unbearable is a question worked out through what follows it: the reformation of assemblages." (Tsing, 2016:158)

Disturbance introduces heterogeneity and, as Tsing stresses, it is 'good or bad' according to what it results in afterwards. Heterogeneity is a key concept for studying landscapes. Terrestrial landscapes are not homogeneous. They are heterogeneous due to many factors and circumstances; they are generated by non-living forces (floods, fires), as well as by living creatures that shape their environment (as in Gaia hypothesis). In addition, although perceived locally the cause for a disturbance may have been triggered elsewhere, and its effects may not be limited to the site where it occurs. Disturbance makes it possible to trace phenomena across borders, as Tsing demonstrates by tracing the mushroom from the Oregon forests in the United States to Satoyama forests in Japan.

Second, by blurring the lines between a good and bad event (morality), human and non-human (species), Tsing outlines some ideas for reconsidering the role of design practice. In her analysis, biotic and abiotic ecosystems form patterns that are organized into assemblages in an unintentional design. The term 'unintentional design' describes the unintentional effects of an action of one landscape's agent on another. The effects are not predefined in advance; they are not controlled. And like mushrooms they can sometimes appear spontaneously or not at all. Their trajectory is not programmed; it is not planned. Vivieros de Castro (2019) recently put forward the same argument to think of "unpredictability" when he compares the way of thinking of an engineer with that of a bricoleur. The bricoleur relies on "already available heterogeneous materials" to create something while the engineer forces the materials into his concept. In the face of the terrible events of the Anthropocene, he suggests that bricolage could be a better way to reverse conventional and predictable assumptions (the inevitable fate of Anthropos), because the bricoleur manipulates unpredictable materials and adapts her project according to the events.

Third, exploring the relationships between various entities composing the forest allows Tsing to escape from the hegemony of the Anthropocene narrative and man as the hero of the story. Tackling anthropocentrism from within, she wonders: "Can I show landscape as the protagonist of an adventure in which humans are only one kind of participant?" (Tsing, 2016:155) Can we take a moment to stop and look around us at what is happening without consider human as the hero of the story? In landscapes, we are drawn into an active space where different elements move at various paces. This is not the place where things happen. Landscapes as we have seen are not given static décors of human activities but they are flows of things in progress, things that happen. The stories that Tsing narrates occur simultaneously, they overlap or coordinate (Tsing and Gain, 2018). Detecting them depends on how we observe them, what we notice, what tools, instruments and conceptual frameworks are used, in order at least, perhaps, to be able to see that these "assemblages are performances of livability" (Tsing 2016:155), as Coccia puts it in a recent lecture (2018). According to anthropologists (Khon, 2013; Morizot, 2016; Myers, 2017), living is a performance, played by several beings. Landscapes are those performances, movements, life lines, life paths (Ingold, 2007). And not only of one species but also lines knotted between several species, a cross-species string figure to be played (Despret, 2012). When there is coordination between rocks, fungus and trees, living *or killing* conditions occur. They perform the act of living, for better or worse, as shown in *Arts of living on a damaged planet* (Tsing, Swanson, Gan, Bubandt, 2017b). This performance allows air to be exchanged by balancing carbon and oxygen, and phosphorus to be distributed. Its repetition means that the same agents are performing again, perhaps not together, but in other partnerships. The fungus has its own way of producing living conditions for itself and the beings with whom it relates. The particular role of human beings is therefore put in question: we are not alone in creating conditions of habitability. Human beings are one kind of actor among many others. Coccia (2018), inspired by what he calls a philosophy of plants, argues that plants are not landscapes but landscapers: "Species design their space and shape space for others as well by doing it. Architecture is not the thing of human beings. It is a more general faculty of species." Plants do not live passively in the world; they constantly build it by releasing oxygen, making soil and creating shelter and food for other species. Thus, if the capacity for conceiving landscapes is extended to non-humans, how are architects and planners to intervene in this landscape? Does this call for a cosmopolitical design where the design of other species will be recognised? What is in fact the state of the art regarding cosmopolitical design?

Architects reclaiming cosmopolitical design consider that many entities network with the human world, as Yaneva and Zaero-Polo (2015) demonstrate in *What is cosmopolitical design? design, nature and the built environment*. Gathering thinkers, anthropologists and architects, the book outlines what could be a cosmopolitical design practice. Drawing on Stengers, Yaneva addresses questions of cosmopolitics. She suggests moving away from the anthropocentric view where designers would only consider one dimension in their design. Instead, she proposes turning every being "into a cause for thinking and to design it in such a way that collective thinking has to proceed 'in the presence of' them" (Yaneva, 2015:4). So, the question is, "How do we make room for others?" (Pignarre and Stengers, 2011). How to take them seriously into account and design with them? This is not only a question of accepting different ontologies: rivers, species, air, pollution, objects, materials; it is also to render explicit in the design the connections we have with them. In this cosmopolitical perspective, designing is not to project a space upon a unified and silent nature, but to take into account, at the pace of the entities' unfolding, the proliferation of species, objects, other agencies: it is about "assembling, composing, redefining, and modifying the composition every time a new non-human is brought into connection with humans" (Yaneva, 2015:16). It is an active process, meaning that as soon as we detect an entity, it enters into the assembly and therefore we should share space with them, as written many years ago in a poem *Marrow* by Ursula Le Guin (1981)[42]. Recently, the Monsoon Assemblage project, led by Lindsay Bremner, addresses the cosmopolitical aspect of what constitute 'the environment', showing its multiplicity by inviting in the conversation « (…) depressions, winds, cyclones, clouds, onsets, temporalities and forecasts; (…) birds, seed dispersal, dust, aerosols and fragrances; (…) » (2021a:2) Bremner frames the cosmopolitical as relationships to the Earth, relying on Latour and Stengers: "for Latour, a politics of contest, deliberation and negotiation to assemble and administer the world that we share with heterogeneous, shifting, human and nonhuman others; for Stengers, how to incorporate earthly forces that we live in intimate relations with yet are inimical and entirely indifferent to the questions we pose them, into our conception of politics and life itself. Thinking cosmopolitically is about acknowledging our constitutive, collective vulnerability to the earth and its rumblings and finding ways to deal compassionately with those exposed to its eventfulness." (2021b:39). Bremner focuses more particularly on a narrative on sediments as the main actors of her "thought experiment" aiming at describing territory through earth dynamic

42 "We must share space with the ghostly contours of a stone, the radioactivity of a fingerprint, the eggs of a horseshoe crab, a wild bat pollinator, an absent wildflower in a meadow, a lichen on a tombstone, a tomato growing in an abandoned car tire. It is these shared spaces, or what we call haunted landscapes, that relentlessly trouble the narrative of Progress, and urge us to radically imagine worlds that are possible because they are already here."

processes bringing together both materiality (the very shape, form, size, scale and process of sediments) and political related human settlements issues: "The paper is framed by questions of how to engage more closely with the dynamics of earth systems and of how social and political agency emerges alongside earth forces" ((2021b:1). Moving through the process of sediment as they flow from the mountain to the ocean, she describes its journey: "For sediments mobilize surfaces and materials, unsettle dry, grounded notions of place and undercut binary notions of geo-physical and geo-political worlds. They remind us that the earth's cycles and matterings are lively, elemental, entangled and emergent, extend our understanding of intra-actions between elements, bodies, space and time, and open the trajectories of human life and struggle to the long durée of planetary cycles." (2021b:26). This echoes Duperrex's book *Voyage en sol incertain* (2019) who describes Mississippi ground and issues by following the granulometry of the sediments and all the entities they bring together which could be humans, insects, plants, industries, and so on. What is surprising in this narrative is the mixture of industrial and natural histories, in a complex interweaving, the industrial and polluted components of the landscape becoming the conditions of life and existence of a whole myriad of plant and animal beings in the delta. One finds oneself immersed in the Rhone delta or submerged in the waters of the Mississippi, through an interplay of spatial and temporal scales, where a species of bird finds itself embedded, almost correlated, with a chemical species or a rock in an uncertain trajectory. What is certain in these uncertain landscapes is the certainty of erosion, of the loss of soils, of the sediments that form the changing soils of the deltas, maintaining this ecotonal fringe between fresh and salt water, making the border an obsolete concept. Everywhere the edges are tightening, as dams are built, imaginary lines are closed. When we lose the deltas we lose our ability to learn to love the shifting, indecisive fringes full of possibilities. The author makes us feel the soft surface of the ground sinking when the fresh water underneath is gone forever, and the salt water, once pushed back by geology or plant rhizomes, threatens to invade and cover the land as it has done many times in the past. Without nostalgia, however, the book bears witness to a current period, through travel notes and meticulous scientific investigation, compiled and superimposed so as not to make us forget the fragile lives that a single wave can swallow. In both cases, Bremner and Duperrex's narratives, space is no longer a background, a stable and fix, immobile, it rather moves and changes, and we need to set new methodology and new narratives to follow this movement.

Some architecture scholars have questioned the place of humans in the environment as something that architects need to deal with. They advocate for practices of care, that is, paying attention to relationships between collectives, humans and non-humans, rather than focusing on architecture as an object (Frichot, 2018; Krasny and Fritz, 2019; Krogh, 2020). However, they do not refer directly to the cosmopolitical as something that brings together the cosmos and the political (Stengers, 2010). There is as yet little fieldwork to provide evidence to support this view. There is here a gap to address. This gap could be correlated to the lack of cosmopolitical visualisations, as we will discuss now.

Cosmopolitical visualisations are constructed, like anthropocentric visualisations. So how are they constructed? In the following pages, we will ask questions similar to those in the section on anthropocentric visualisations: what is the point of view from which these visualisations are constructed? With what 'tools'? For whom and for what purpose?

The anthropocentric view aims to escape the ancient cosmos as Koyré's famous axiom "From the Closed World to the Infinite Universe" (1968) reminds us, to launch out into progress and dream of an omnipotent vision. This vision claims to stand alone, detached from earthly conditions. However, a careful analysis of how the visualisations of the Globe are made invalidates this statement. Claiming a divine point of view, especially through maps, is likely to fail as soon as we look behind the scenes, as Nagel (1986) suggests. Even the globalised Earth is a *constructed* Earth; the dimensions and the qualities of the cosmos are always calculated somewhere, in more and more connected and numerous observatories or at the U.S. National Aeronautics and Space Administration (Grevsmühl, 2014; 2016). It is always possible to retrace the global production chain through the mediators that build the map, whether through places, technologies or people and their network. Thus, what is global has always been decided in a room on Earth. The global is an illusion that has the particularity of having lost the actors who produced it. On the contrary, if we follow the connections, we are able to relocate the data each time, as demonstrated by recent publications that dissect the impact of aerial views on the territories[43].

This means that we depend on instruments to obtain visualisations of the world, whether it is to observe large or small objects. As Aït-Touati (2011; 2012) tells us, in 1665, scientist Robert Hooke set out to rediscover the world through his optical instruments. Through the compound lens of his microscope, he proposed to see a minuscule and unknown world: the magnificence of insects or mold landscapes. In the meantime, he had to go through the process of drawing to report on these now-visualised observations, as do all scientific reports (Latour, 1986). Visualisations, understood both as an instrument to see and as a drawing of this vision, are therefore not only descriptions but also constructions of the idea of nature. A view is therefore always situated somewhere. There is no external point of view; it is always a view from the 'inside' (Haraway, 1988). But this situated view is often criticised as not being 'objective'. What about the real meaning of objectivity? In the book *Objectivity*, Daston and Galison (2007) retrace the history of objectivity's emergence. The process of gaining objectivity, that is, of visualising nature's processes as accurately as possible, varied throughout history, depending on relationships between scientists, artists, instruments, and drawing techniques. Consequently, objectivity is always a moving construction across historical periods. However, the search for objectivity developed a set of scientific practices as Daston writes: "Articles circulated across oceans and continents, measurements were exchanged, observations recorded, instruments calibrated, units and standardized categories" (1992:608). She continues: "It would be exaggerated, but not distorted, to claim that it is scientific communication that is the prerequisite for the uniformity of nature rather than the other way around" (ibid.). Thus, not only has science defined its own procedures for validating facts, but it has also defined its object of study, i.e. nature itself.

As a result, this new scientific instrumentation would have selected

43 The London-based group Forensic Architecture for instance criticizes power by subverting aerial maps of territories at war.

certain features of nature while setting aside others when constructing the very idea of nature. If we forget this construction, these practices, it seems that nature 'stands on its own'. Yet, as the man who is considered the founding father of modern earth sciences, Humboldt, reminds us, it requires considerable effort to take instruments into the field for the purpose of making measurements and recording them on drawings. The idea of nature is constructed in the field and through the instruments brought along. Humboldt's travels are described in his memoirs, *Tableaux de la Nature* (1850), a scientific report of the explored territories where he describes specific geographical, geological, climatic and botanical situations. Each description is linked to a journey he had undertaken on foot, with collaborators, often carrying cumbersome instruments. We follow his travels throughout the book. It was the Earth before the *res extensa*, the abstract concept that contribute to the homogenization of places as if everything was continuous, as the idea of the globe latter suggests. On the contrary, according to Laura Dassow Walls (2017; 2020), the specific narration used by Humboldt make sense of the Earth as a world not by a global homogenization but through recursive loops that progressively draw connections between distant places[44]. Past cartography was much more than just a geospatial survey as we know it today: it was accompanied by stories and surrounded by drawings, not as annexes but central to understanding the landscape: species, instruments, atmospheric variations, internal movements of the earth, etc. In a contemporary version, the Earth is now also monitored by sensing devices, covering larger or smaller parts of the land and oceans (Gabrys, 2016; 2020). However, as Stengers (2020) reminds us, we should be cautious of Gaia: the Earth would not be so easily watched, in a warning to not simplify the observations, advocating for what could be 'earthly sciences', accounting for a 'folded' Earth.

If we look at scientific visualisations, we can see that the instruments are central. They also situate the designer of the visualisation in a specific place. This is a first step in understanding what a cosmopolitical visualisa-

44 According to Laura Dassow Walls, Humboldt's "narrative movement is not a smooth progress, but proceeds through multiple loops, out and back. One loop structures the book's narrative arc (from ocean, to inland, back to ocean); smaller loops structure the essays, down to loops within loops. Each loop adds to the connective fabric of the whole, growing the connections between any two points until the planet has grown beyond all bounds, showing itself in all its staggering immensity, variety, and depth."

tion might be, by recognising practices that construct a view from their own perspectives, from within. The historian of science Tresch has a name for this: he calls it a cosmogram. This concept will lead us to this question: for whom are cosmopolitical visualisations made and to what end? Cosmogram visualisations, more than constructing a reality, embrace the ontological complexity of reality. For Tresch (2005; 2007), a cosmogram is the artefact that embodies the relations between humans, God and nature, according to the ontology of a society. The cosmogram materialises a cosmography through objects, texts or maps and results in a concrete practice that allows humans to act according to the community's world view, enabling people to bring themselves into agreement. Cosmograms are therefore "interpretations and actions: social relations, relations with other cultures, with natural entities, with animals, plants – but it also establishes the relation between different domains or ontological levels – the mundane world, the world of spirits, God and the ancestors, places where they intersect". Worlds come with attachments and are built by various means of expression. For Tresch, the redescription of worlds suggests "not the world as it is but the world as it could be". Then, "Cosmograms often guide this recreation and stabilisation of the world. They might proclaim permanent structures, or they might acknowledge their own fluidity and contingency" (Tresch, 2005:74-75). Cosmograms are thus developed from within collectives. Drawing, thinking about new cosmograms is necessary to shape new relationships with the Earth: "The question of how to represent our cosmos not from outside and above but from below and within is all the more pressing as we see how naturalism accelerates extraction and consumption, making our every action another blow against the planet (..)" (Tresch, 2020:68) Thus, the cosmogram is a compositional tool for making worlds, placing the concerns of individuals within a broader social, national or community framework.

To better understand this notion, we can examine the process of making sung maps: the cosmogram of a non-western collective, the Australian Aborigines. The aim here is to recognise the diversity of what a cosmogram might be compared to Western cartographies. According to Australian aborigines, the topography of a site would have been formed by the impact of giant beings who, at the time of the myth, lived on Earth and fought.

Falling to the ground, a giant created a crevasse. Others, while fighting, threw huge rocks which upon impact with the ground dug water reservoirs[45] (Descola, 2008-2011). In this chaos, beings already have characteristics. A huge snake slid across the territory; its footprint carved a riverbed between the mountains. Human and non-human are distributed throughout the territory and are attached to each being who has shaped it: it is their totem, a prototype[46] (Descola, 2001-2004). This cosmogram is embodied in an oral travel map. Each story is transmitted orally from generation to generation in a song which, if this song is memorized, allows everyone to find their way around this flat and desert territory. This song is indeed a map which embodies a particular ontology (Descola, 2021), the peregrinations of beings corresponding to very precise elements of the topography, to water points, vital elements that put us in danger if they are not known. Landscape is therefore not “the representation of a portion of a country embraced by the view from a fixed point in which landscape representation usually consists, but of the representation of possibly interconnected morphogenesis paths without ever being integrated into a homogeneous space” (Descola, 2008:531). The resource is to be preserved, the ‘song/field’ of lines is much more than an observation, it is the description of essential subsistence relationships with a landscape. Therefore, cosmopolitics is the way in which a collective of humans and non-humans defines its relationship with the Earth. (Descola, 2017). From this cosmopolitical view, nature is inseparable from cultural considerations, constituting not only human society but also human and non-human relations. It forms a whole, a world, connected by the arts, myths and songs in a practical way since it is in fact a field of resources. Not resources to be extracted but rather protected, valued, hidden and consumed sparingly because they must last over time for future gen-

45 During the genesis of the world, in the “Dreamtime”, “hybrid beings emerged from the ground at specific sites, experienced many adventures during their peregrinations on the surface of the earth, then sank into the bowels of the earth; the actions they carried out resulted in shaping the physical environment, either because they metamorphosed into an element of the landscape, or because a trace of their presence remained in the landscape, so that the characteristic features of the environment bear witness to these adventures to date.” p525

46 “In many tribes, the main totem pole of a group - a natural species, an object, an element of the landscape, a substance or a part of the human body - and all beings, human and non-human, affiliated with it are considered to share physiological, physical and psychological properties by virtue of a common origin and located in space.” p564.

erations and for the other beings, animals and plants that live from them.

The cosmogram is not a unique, objective version of what should be the reality. Instead, cosmograms convey the idea that there are different constructions of the world by different collectives. Following James' pluriverse (James, 1909), anthropologists Viveiros de Castro (2014) and de la Cadena, Blaser (2018), claim there are multiverses as they observe different collectives. Similarly, in "Plato and the Simulacrum" from *The Logic of Sense* (1983), Deleuze states that not only do many points of view produce several versions of the same world, but that these points of view produce indeed several worlds that are call versions[47]. Therefore, there is not an Ideal, a good *re*presentation of a *true* reality. The normative Ideal is opposed to the Simulacrum (Deleuze, Krauss, 1983), understood as a distortion of the ever-reactualised reality. Simulacra do not aim to access a single reality but are distinct versions of the world. Philosopher Manigliere (2014) explains these possible versions more concretely, referring to Deleuze: "The Earth is not a transcendent identity; it is the dynamic of the diverging versions of itself. The Earth therefore only exists because it makes sense to say that the entity uncovered by the IPCC reports and the "great earth-forest" presented by Amazonian shaman Davi Kopenawa are indeed continuous with one another, which means that we have to understand how one becomes the other, without anyone being a metaphor or just a representation of the other one" (2014). Cosmopolitical views are versions of reality, whereas the anthropocentric view is based on an ideal single reality. In this type of visualisation we see little but we see it well; this is what Latour (2005) means by oligoptic vision. The oligoptic regime of observation gives us access *within* the cosmos, which we retrace through a meticulous description of its components.

In contrast to the anthropocentric view, the cosmopolitical view does not place man at the centre of the debate but among other entities. As we have seen, this vision is very close to the Gaia Hypothesis, which inspired the original cosmopolitical thinkers. However, this cosmopolitical view is less

47 "It is in no way a question of different points of view on a single story understood as the same, for these points remain subject to a rule of convergence. It is, on the contrary, a matter of different and divergent narratives, as though to each point of view there corresponded an absolutely distinct landscape." p51

well known in spatial practices and design theories. We have also seen how relevant it is to think of landscape differently in the uncertain times in which we live. Moreover, we identified a lack of visualisation of the cosmopolitical. The modes of representation in use still revolve around an anthropocentric view. Drawing on accounts of historians of science, we examined what cosmopolitical visualisations are and how they could be constructed. They could be designed with the help of instruments that offer a view of nature from the inside, as cosmograms that shape the reality of a collective.

2.6 Conclusion: towards a compositional view from within?

The view that has dominated social sciences and human geography is the *anthropocentric view*. It considers nature as a resource, something out there, passive and extractable for human purposes. This view strongly influenced the field of architecture, planning, and the practices of designers. On the contrary, the *cosmopolitical view* is less known. Therefore, the consequences for design have not fully been drawn. In this view, landscape is an assemblage composed by many entities interacting in complex ways. To provide an alternative understanding of landscapes better attuned to recent studies of climatic developments, it is necessary to develop the cosmopolitical view and its visualisation.

Through the analysis of the literature, we have been able to identify the main obstacles to a cosmopolitical view of nature.

First, landscapes are taken for granted so that their composition is not questioned. The entities of the landscape considered as meta-objects in the anthropocentric view - soil, river, tree, atmosphere - are challenged by the cosmopolitical approach which advocates a more granulometric viewpoint in the search for the different agents composing the environment. Moreover, the Gaia hypothesis states that 1. these agents actively modify their environment and are not a passive background as previously assumed in the pre-conceived notion of landscape; and 2. that matter is animated chemically and physically, either directly by a living being (soil generated by worms for example), or indirectly by passing through a living being to become (rocks). What then constitutes landscapes? How can we notice them, observe them? How can we give a more precise description and then a better visualisation?

Secondly, we identified a lack of approaches assuming views "from within". The Anthropocene could result from a misconception of nature outside society, from which we can extract materials and transform them into resources. What hinders cosmopolitics is also a lack of collective concern for the agents and processes that make up the territories. To bring these collective concerns together, we do not even have a common visualisation that is different from the dominant capitalist and colonial maps originally made to define borders. The anthropocentric view prevents us from understanding these transformations and the intrusion of Gaia. Moving away from extraction and disaffiliation, Gaia requires thinking about involvement, folding, superposition, and interlocking. Cosmopolitical visualisations suggest seeing 'from within', that is, shifting from the usual aerial cartographic view of space to a much more concrete, dynamic, complex, heterogeneous and reactive Earth than the cartographic imagination of points defined on a map by longitude and latitude can capture. How then to acquire this view from inside? With which instruments, points of view? To whom could it be addressed?

In order to answer these questions, this dissertation suggests defining landscape entities in a different way and then experimenting with new types of visualisations from the inside. To achieve this objective, the methodology adopted is to follow the natural sciences-in-the-making within a network of scientists and their observatories studying the Critical Zones, with the main interest being to anchor and situate Gaia in the territories. Thanks to this fieldwork developed through the empirical chapters, we will shed light on their understanding of nature. Ethnographic observations seem to be the most appropriate way to be close to this relatively new field of research (sites and practices) and to understand its complexity (chemistry and geology). The choice of methodology will be discussed in the following chapter.

3 Following the scientists in the Critical Zone

3.1 Introduction

To understand how Gaia's intrusion changes landscapes, we should not ask *what* this alternative understanding of nature is, but *where* can we trace this knowledge in the making. Thus, we need to situate our study in local places where we can record the disturbances caused by human activities which trigger these changes. Therefore, I approached the scientific network of Critical Zones because they study how the Earth reacts to changes through a network of outdoor laboratories called Observatories (Latour, 2014). The Critical Zone (CZ) is the thin layer of the Earth, a space or volume from the deep rocks to the tree canopy which is modified and maintained habitable by living beings. The CZ is the product of chemical weathering and erosion, occurring when the water transfers chemical elements through rocks that will eventually form fertile soils. It is, more importantly, our habitat (Gaillardet, 2020). As these processes are poorly understood in terms of reactions, variations and evolutions, an interdisciplinary scientific program of the Earth has been initiated to study them. The Critical Zone science involves a network of geoscientists aiming collectively to understand the impact of the Anthropocene (drought, storms, pollution, soil depletion, etc.) by studying complex cycles at the interface of soils, atmosphere and rocks. The scientists work in observatories as new research infrastructures, following the US network founded in 2001. They implemented local outdoor observatories located at different places on Earth (Brantley, Goldhaber and Ragnarsdottir 2017; Richter and Billings 2015; Brantley et al., 2017; Gaillardet et al. 2018) (Fig.1). An observatory is set in a watershed[48], which is not an administrative territory here, but a geological entity in which water circulates. It becomes an

48 A watershed or drainage basin or catchment area is, in standard geoscience knowledge, an "area of land where precipitation collects and drains off into a common outlet, such as into a river, bay, or other body of water. The drainage basin includes all the surface water from rain runoff, snowmelt, hail, sleet and nearby streams that run downslope towards the shared outlet, as well as the groundwater underneath the earth›s surface. The drainage basin acts as a funnel by collecting all the water within the area covered by the basin and channelling it to a single point. Each drainage basin is separated topographically from adjacent basins by a perimeter, the drainage divide, making up a succession of higher geographical features (such as a ridge, hill or mountains) forming a barrier." https://en.wikipedia.org/wiki/Drainage_basin

observatory when equipped with instruments that register the dynamics of the Critical Zone (Fig.2). In these outdoor laboratories, also called Critical Zone Observatories (CZOs), the scientists study geomorphology, water circulation and chemical exchanges, such as the circulation of carbon, nitrates, phosphorus, sulphur, and how they are disturbed by human activities. A CZO is thus a monitored environment equipped with scientific instruments from which data, samplings, are collected and brought to indoor laboratories in buildings.

My fieldwork mostly took place in the French CZ network. The CRITEX research programme, Innovative Equipment for the Critical Zone, has enabled the establishment of the Critical Zone network in France by funding the development of new observation instruments. CRITEX[49] is one of the 36 equipment programs funded by the "Plan d'investissement pour l'Avenir" initiative of the French Government in order to improve French competitivity and was awarded a total of 7 M€ from 2012 and for seven years. It is managed by CNRS under the scientific leadership of the two French networks RBV and H+ (Réseau des Bassins Versants and réseau des sites hydrogéologique respectively). This vast instrumentation programme for existing observatories that had previously few exchanges between them made it possible to unite them around a common objective: the knowledge of the CZ. Thus, OZCAR[50] was created and allowed the recruitment of thesis students, the hiring of post-docs, exchanges with international scientists. A white paper established the OZCAR network in the country, created by Jérôme Gaillardet and then comanaged by Isabelle Braud: "OZCAR: le réseau français des observatoires des zones critiques" in 2018. However, most of the scientific literature referring to the Critical Zone in the

49 CRITEX (Challenging equipment for the temporal and spatial exploration of the Critical Zone at the catchment scale) is an instrumental project aiming at buying and building innovative instruments for better understanding and scrutinize the Critical Zone of the Earth. It is viewed as a shared analytical facility supported by all French research institution involved in environmental studies (CNRS, INRA, IRSTEA, IRD, BRGM) and 15 universities aiming at equipping the Critical Zone observatories of a new generation of performing sensors. CRITEX aims to develop new sensors and to deploy commercial instruments in well chosen Critical Zone observatories by fostering collaborations between disciplines and approaches (i.e. geochemistry and geophysics or hydrology). Instruments may be a good way of reconciling the dialogue between disciplines in the Critical Zone. https://www.critex.fr/what-is-critex/critex-why-and-how/

50 OZCAR = Observatoire de Recherche sur la Zone Critique, applications en recherche.

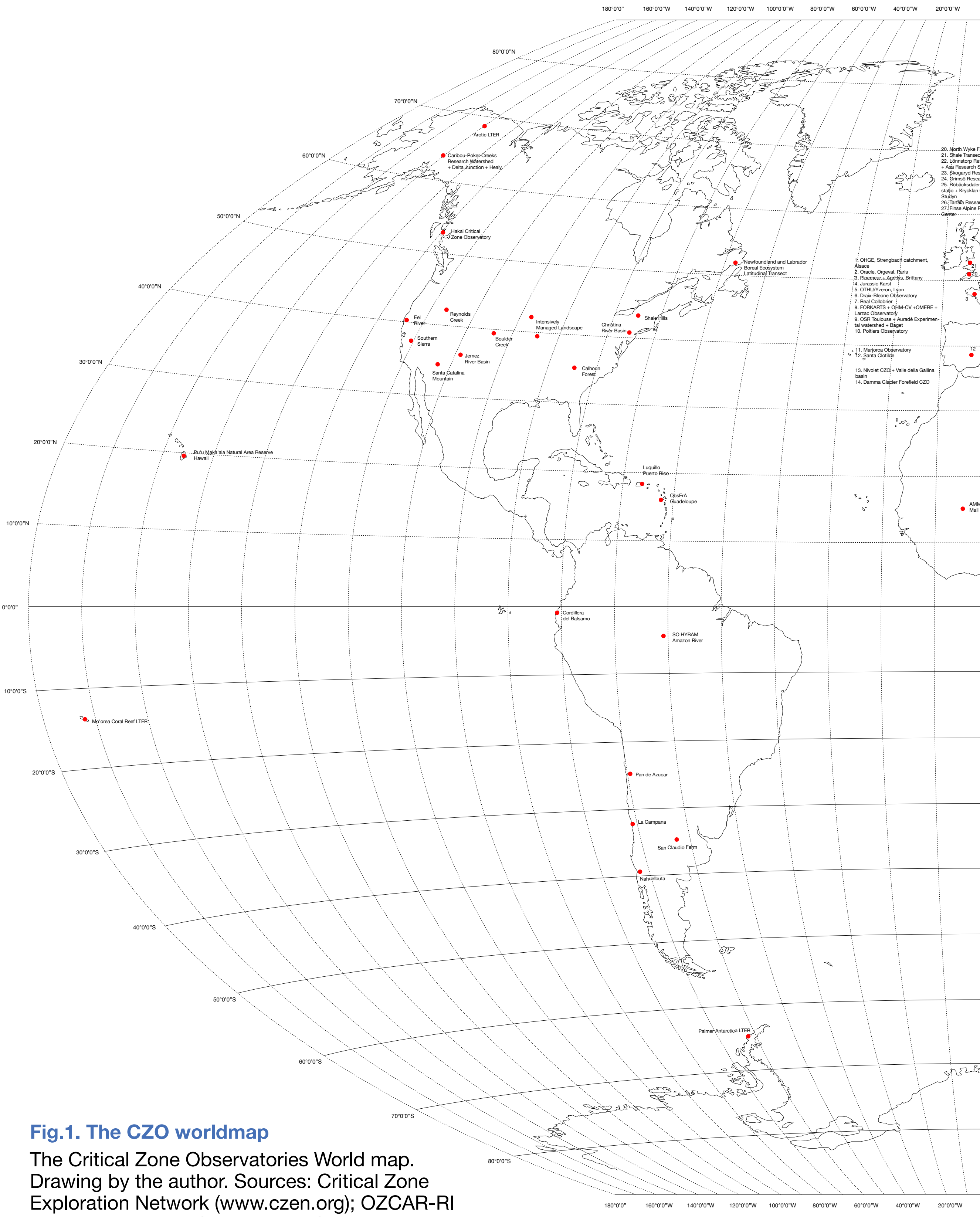

Fig.1. The CZO worldmap

The Critical Zone Observatories World map. Drawing by the author. Sources: Critical Zone Exploration Network (www.czen.org); OZCAR-RI French network of Critical Zone Observatories (www.ozcar-ri.org); TERENO German Terrestrial Environmental Observatories (https://www.tereno.net) ; National Critical Zone Observatory US (http://criticalzone.org/national/).

15. Pre-Alpine Observatory. KIT
16. Eifel / Lower Rhine Valley Observatory. FZJ
17. Harz / Central German Lowland Observatory. UFZ
18. Northeast German Lowland Observatory. GFZ
19. Fuchsenbigl-Marchfeld CZO, Austria
Leeds farm
Iznik Basin
OMERE Tunisia
Koiliaris River Basin CZO
Lhasa Plateau Ecological Research Station
Ganga Basin CZO
Hyderabad Observatory
Western Ghats
M-TROPICS/BVET India
M-TROPICS/MSEC Vietnam
AMMA-CATCH Niger
AMMA-CATCH Benin
M-TROPICS/BVET - Cameroon
Lopé National Park CZO Gabon
Mayotte
La Réunion
LHC Flux Site + NCU Atmospheric and Hydrological Observatories (NAHOs) - Taiwan
Baru Experimental Watershed
28. Southwest Karst CZO
29. Chenqi CZO
30. Sanming Research Station of Forest Ecosystem and Global Change
31. Qianyanzhou Agricultural Experimental Station
32. Red Soil (Sunjia) CZO
33. Changshu AgroEcological Experiment Station
34. Jianghan Plain CZO
35. Taoyuan Agricultural Ecological Station
36. Yanting Agricultural Ecological Station
37. Loess Plateau CZO
38. Fengqiu Agricultural Ecological Station
39. Yucheng Integrated Agricultural Experimental Station
40. Luancheng Agricultural Ecological Station
41. Liudaogou watershed
42. Luan River CZO
43. Shenyang Experimental Station
44. Black Soil CZO
45. Hailun Agricultural Ecological Station
46. Baeg-nyong (BN) Cave CZO + Punch Bowl (PB) CZO
FNQ Rainforest- Robson Creek
Litchfield Savanna
FNQ Rainforest- Daintree
Alica Mulga
SEQ Peri-urban SuperSite - Karawatha + Main Range Critical Zone Observatory
Great Western Woodlands
UWA CZO - Avon River Catchment
Calperum Mallee SuperSite
Cumberland Plain
Tumbarumba Wet Eucalypt
Victorian Dry Eucalypt SuperSite - Whroo
Victorian Dry Eucalypt - Wombat
Warra Tall Eucalypt
McMurdo Dry Valleys LTER
80°0'0"N
70°0'0"N
60°0'0"N
50°0'0"N
40°0'0"N
30°0'0"N
20°0'0"N
10°0'0"N
0°0'0"
10°0'0"S
20°0'0"S
30°0'0"S
40°0'0"S
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70°0'0"S
80°0'0"S
0°0'0"
20°0'0"E
40°0'0"E
60°0'0"E
80°0'0"E
100°0'0"E
120°0'0"E
140°0'0"E
160°0'0"E
180°0'0"

titles is North American, including a book *Principles and Dynamics of the Critical Zone* by John R. Giardino and Chris Houser (Texas A&M University) in 2015. Numerous other articles on this paradigm have been published (Brantley, Goldhaber and Ragnarsdottir 2007; Richter and Billings 2015). In the context of a collaboration between the United States and Europe, an article "Sustaining Earth's Critical Zone" was co-authored by many scientists (including Gaillardet and Banwart) in 2013. The few publications and my field experience confirm the fact that the CZ did not and still does not have a stable definition. It is a network in the making. Its definition evolves rapidly, shaping itself as it is studied. The newsletter edited by OZCAR network each season were very useful to understand this dynamic and what kind of research is done in each observatory. In France, the scientific papers mention CZ as a paradigm but it is not their direct subject. These very specialized articles on geochemistry, geophysics, etc. were often very difficult for me to read, which is why I did not really rely on them for my empirical data and relied more on ethnographic observations and interviews. However, the diversity of these articles shows that CZ is not a unified knowledge and that it is rather used as a gathering concept and not as a fixed methodology to be applied to research. The recent exhibition catalogue dedicated to the Critical Zones (Latour and Weibel 2020), offers a chance to the scientists to disseminate their research into other fields. On Latour's demand, some Critical Zone scientists were invited to write articles about their work and give their view on what is the Critical Zone (Gaillardet, 2020; Pierret, 2020; Brantley, 2020; Banwart, 2020; Richter and Billings, 2020). As it will be shown through the following empirical chapters, there is not a generic science describing the CZ, but instead a diversity of practices which nevertheless share some common definitions and methods. This was very useful for me to understand when I started to follow scientists in the field and witness the diversity of their practices.

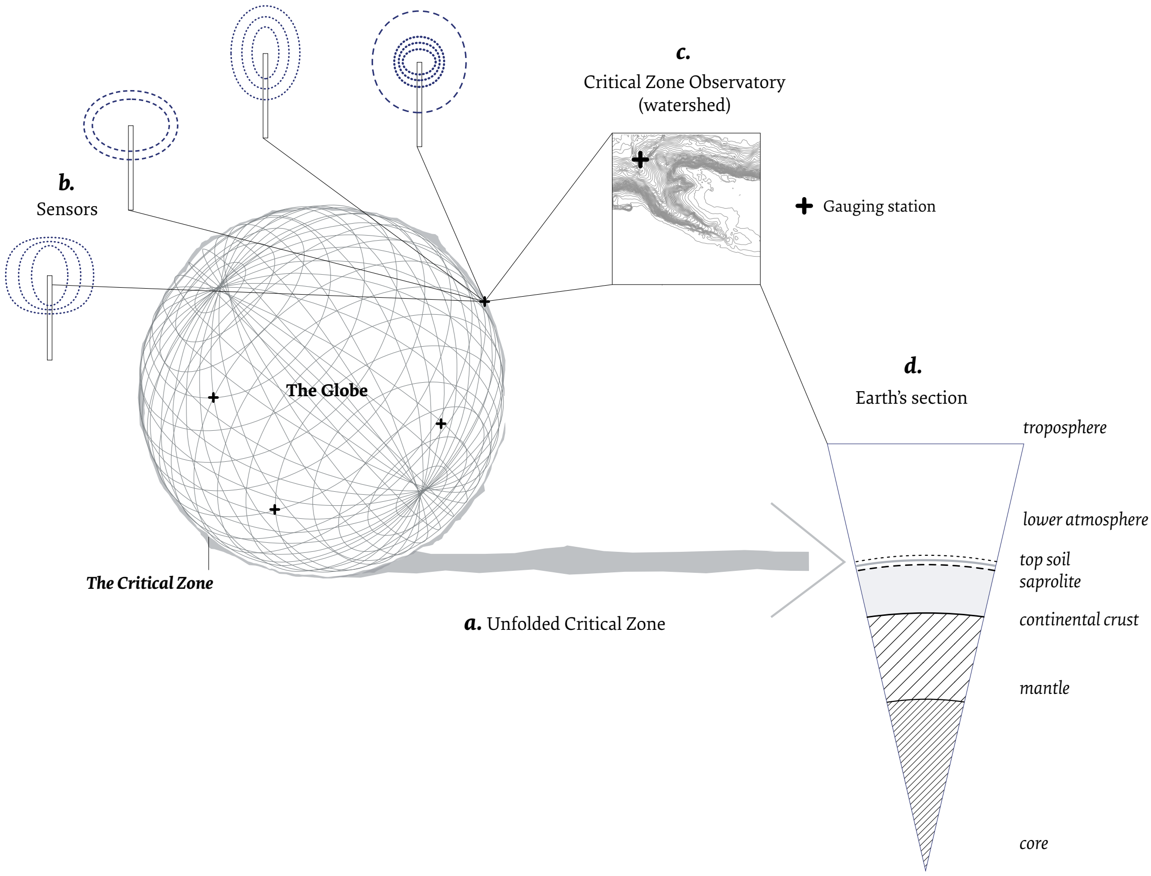


Fig. 2. From a global to a 'Critical Zone' perspective

The Critical Zone (CZ, Figure 2a) is a thin pellicle at the Earth's surface where life and human activities are concentrated. To deal with its large heterogeneity on the globe, scientists have designed local 'Critical Zone Observatories' (CZO, Figure 2c), such as watersheds, equipped with sophisticated sensors (Figure 2b) monitoring the local CZ continuously and for long time periods, gathering data for different parameters used by scientists in conceptual models. Figure 2d shows, of course not at the right scale, from the top of the troposphere to the Earth's center, the position of the CZ in a classical geophysical description of the Earth.
Drawing by the author, published in the Anthropocene Review (Arènes et al. 2018)

In this methodology chapter, I describe how I approached the fieldwork in the Critical Zone and how I organised it, what kind of methods were used, what kind of data it provided and why it is interesting. Ethnographic observation was the main method used, supplemented by semi-structured interviews and 'ethnographic field interviews'. The fieldwork was organised in two different sets of locations: the (outdoor) field which encompasses many locations (France, West Indies, USA) and the indoor laboratories where the scientists have their offices (France).

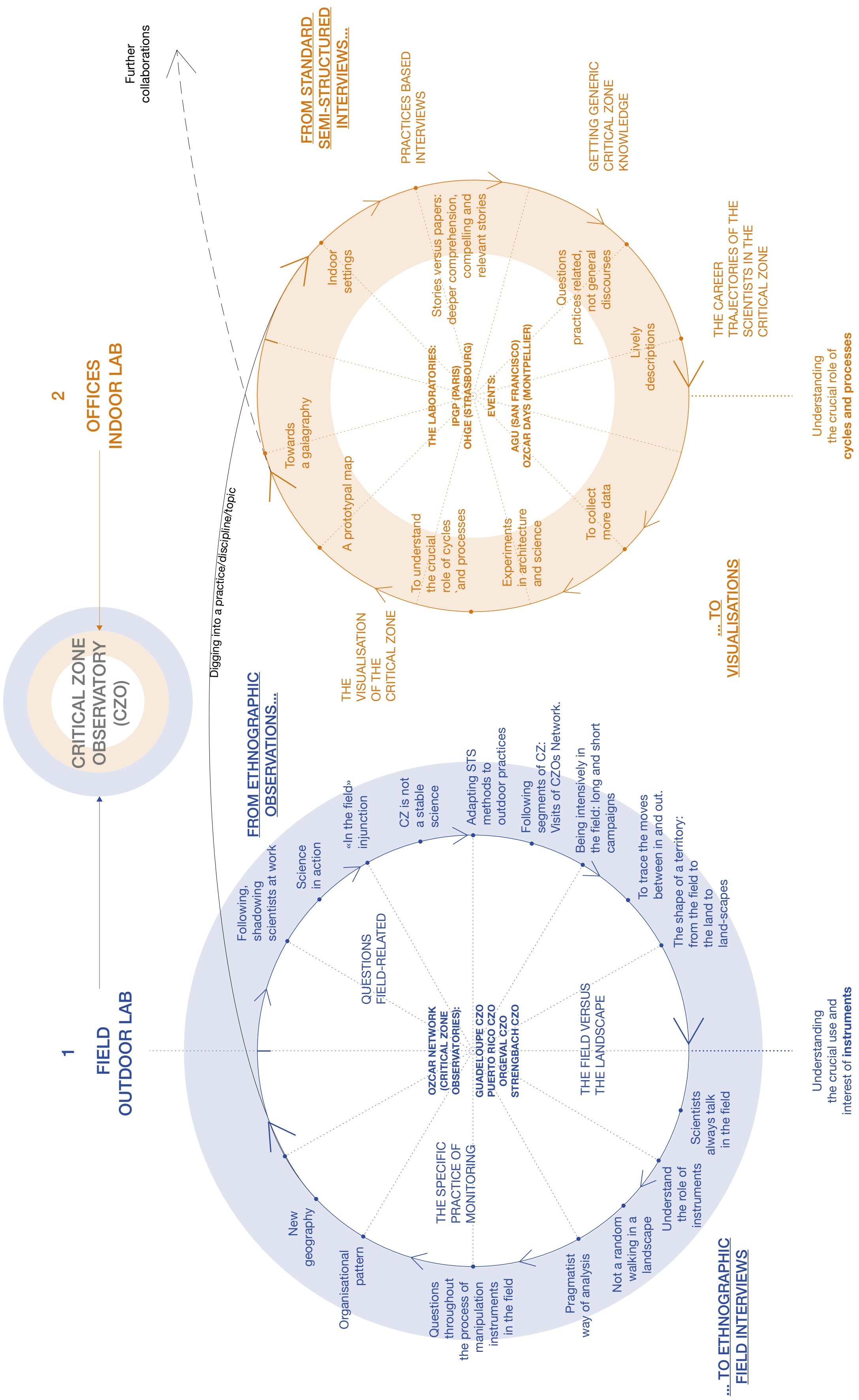


Diagram 2. Methodology

3.2 Ethnographic observations

To study the Critical Zone network, I used ethnographic observations. This methodology, informed by STS, Science and Technology Studies, and ANT, Actor Network Theory (Latour, 2005; 2013), has in the past twenty years shown efficiency to grasp science in action. As Yaneva writes: “science studies suggested that the knowledge about a central and insolvable problem could be gained by knowing the local and empirically traceable ones, following and accounting the networks of activities” (2009:24). This methodology consists in following scientists in their daily practices, shadowing their moves to understand how they generate and stabilise knowledge. It allows to trace science in the making by following the practices and the trajectories of the various actors, humans and non-humans alike. Ethnographic observations require the researcher to slow down to be able to notice the details and the gestures of the actors (Yaneva, 2018). With this methodology, I followed the scientists’ moves in the Critical Zone: exploring the field, noting measurements, moving instruments, collecting samples, returning to the lab, storing, analysing, changing methods, drawing graphs, etc. It enables to trace the chain of actions and the procedures that the scientists follow from the field to the lab and back (Latour, 1988). Scientists’ relations with the field are mediated by the instrument. Thus, STS researchers study instruments as they capture phenomena that are usually invisible. Similarly, my fieldwork in the CZ will show the importance of instruments. This fieldwork is also grounded in particular places, local observatories or laboratories, from which scientific knowledge is shaped. It thus contributes to the “localist turn” in sciences studies (Shapin, 1998), focusing on the local production of science making, and the recent attention to urban context and architecture (Galison and Thompson 1999; Yaneva 2018). Moreover, it draws on STS in ways that expand their methods to architecture of science (Yaneva, 2005, 2009; Latour & Yaneva, 2008), and further into landscape ethnography (Tsing 2004, Bubandt and Tsing 2018). This methodology requires a particular kind of attention to the field, and the practices of *site-ing* (Yaneva and Mommersteeg, 2019), that is ethnographic observations that focus on what unfolds through the site, following all its constitutive materials.

The reader will therefore see scientists in action throughout the thesis. While they are important in understanding the Critical Zone and therefore the Earth in the Anthropocene, they are not the heroes of this story. Scientists relay the narrative of the Critical Zone, but the real protagonists are all the elements that make up an environment and act as 'landscapers'. But these composite elements are currently invisible, covered by the general concept of landscape, which thus appears as a black box that we have to open. Ethnography is a method with its own history and disciplines. Drawing on these methods from authors such as Descola (2005), Latour (1982), Tsing (2015), or Viveiros de Castro (2014), this thesis adapts these research methods to provide knowledge for the purposes of architectural research. Scientists are followed closely in their outdoor practices most often, which is why the fieldwork methods shared by the above authors are so important here. However, the focus of this research is not directly on the relationships between scientists but mainly on their relationships with the material world they study, their relationships with the instruments that provide them with new perspectives, new lenses to see the world, as well as the relationships with the field and the laboratories that structure scientists' practices. Here, it is the environment that is studied. Thus, the scenography of the chapters of the thesis follows a particular agenda, different from what might have been done by a social scientist for example, as we seek to understand how landscape entities are understood and traced differently from those we use in design practices, by scientific practices and how this might change architects' design practices. Therefore, as an architect, the research is directed towards a specific question stated above. A social scientist might have produced a different report on the CZ. The report I present as an architect using ethnographic methodologies to access knowledge of the CZ is situated, not only spatially but also professionally. Situated knowledge, according to Haraway (1988), is the only way to access knowledge from within. There is no 'objectivity' without a point of view, which necessarily comes from somewhere. So my relationship with scientists is also shaped by being an architectural researcher and presenting myself as such, using visualisations, diagrams, to discuss with them. In some cases the initial diagrams were co-produced with the scientists, to give an example of how a science-design collaboration could be undertaken.

Therefore, this thesis is not a conventional work of sociology of science that would aim to unpack the process of fabrication of facts. Rather, it extracts knowledge in the Critical Zones in order to shed a different light at the environment for architects. By learning from Critical Zones, the thesis attempts to open that black box of Western landscape tradition which is used in architectural design. Indeed, I started the fieldwork as an architect having always perceived the soil, the atmosphere, the river, the trees, the forest, etc. as preconceived notions, little discussed, and represented in the standard iconography of architectural projects or according to existing mapping methods. Architecture, landscape architecture or design are taken together as a single practice of shaping spaces by integrating the socio-technical parameters and the material world that are now being affected by the new climate regime. From my former practice as an architect in a landscape and urban design firm, as mentioned in the prelude, I notice that the same process is engaged and that each sub-discipline is confronted with the urgent and burning issue of the environmental crisis. This thesis hypothesises that we are helpless in the face of this crisis because we lack material, granular and plural descriptions of the entities that compose the Earth, the landscape, the project sites. This type of knowledge could benefit the entire discipline of design at all scales (landscape and land architecture, city development, building design), each of which needs to deal with notions of soil, water or air in a more active way than before. During the fieldwork, I discovered completely different ways of understanding these entities. It is this experience that I aim to bring back to the field of architecture.

Nevertheless, these human protagonists who introduced me to the Critical Zone deserve an introduction themselves! My main informant in this journey into the Critical Zone is Jérôme Gaillardet. I first met Jérôme in his office which is big enough to contain a meeting table, a wall bookcase and his workstation with a laptop. Books, magazines, plant and rock samples fill the tables **(Fig.3)**. A coral and a piece of two-coloured sliced rock are two of Jerome's fetish pieces **(Fig.4)**. He shows them off with relish whenever he welcomes someone who is not yet familiar with the Critical Zone and therefore needs to be converted. Coral and rock complement each other in explaining the earth process. The first rock has a yellow porous envelope around its solid matter. The second element is a coral with a shape like delicate petals. How are these two elements related? In fact, the yellow part of the first rock is an area where minerals have been lost, washed into the sea, where they are captured by other beings: corals! These two objects illustrate how the earth recycles, transfers materials and minerals to create new life forms. Jérôme Gaillardet is an internationally renowned geochemist and river geologist. He introduced the concept of CZ in France through his links with American researchers, thus helping to propagate this approach. He leads a laboratory called "geochemistry of the external envelopes" at the prestigious Institut de Physique du Globe (IPGP) in Paris, where I have met the scientists of the network working there: Sylvain Pasquet, Paul Floury, Julien Bouchez, Eric Gayer, Pascale Louvet. From this point, I travelled through the network meeting more scientists: Marie-Claire Pierret, Jacques Hinderer, Nolween Lespages, Solen Cotel, Sylvain Kuppel, Lou Derry, Charlotte Le Traon, Jean Marçais, Bill MacDowell, Jennifer Druhan, and many more informally. Ethically, every interview, photo, video or diagram or use of images of the scientists has been discussed and approved by them with the University of Manchester form read and signed by them. The use of names is also agreed by each scientist. The scientists observed were not predefined by myself, but depended on each observatory I visited, following the fieldwork and the opportunity to be with the scientists in the field. Nevertheless, ethnographic study offers a wide range of scientific genres and careers at different levels, from students to professors. CZ science is international, so different nationalities are represented, even if it remains largely Western. I followed these scientists in the labs but also in the field, in the Critical Zone Observatories. The results of the ethnographic observation show that scientific knowledge is not only about measuring but also about using and integrating qualitative and embodied dimensions to their object of study. In contrast to a study of scientific data, here the study of the scientists themselves, from what they told me, shows a sensitive knowledge that is also intuitive in the scientific questions asked of the Earth itself. I was able to collect the scientists' thoughts on the nature of the CZ and thus provide a narrative for the soils, the river or the atmosphere that are the real protagonists of this thesis. Therefore, I chose to focus on ‘expert knowledge’, a term borrowed from Stengers (2010), because it was sufficiently rich. This leads to limitations of the study (exclusion of non-expert forms of knowledge) which will be discussed in the conclusion of the thesis.

The field and the laboratory have been studied in science and technology studies (STS), but often separately, focusing either on the facilities of the laboratory buildings (Latour and Woolgar 1979; Latour, 1982), showing how laboratories give power by changing the scales of the elements studied and reversing the forces; or on the exterior (Latour on soils, 2000; Law and Lynch with birds, 1988; Star 1983, 1989), examining how the environment becomes a lab with all its power attached when the scientific procedures are followed outdoors. Thus, the specific field/laboratory relationship we witness in CZOs deserves special attention. The complementarity between a conventional indoor laboratory and an outdoor laboratory means that both must be reconfigured to allow for this back-and-forth movement. Scientists have to navigate between the field and the laboratory. So I had myself two types of places to study: the outdoor laboratory, which I call ‘field’, and the indoor laboratory, which I call ‘offices’.

Fig.3. Jerome's office, IPGP

Jérôme Gaillardet's office at the IPGP in Paris (Institut de Physique du Globe). Photography by the author.

Fig.4. The rock and the coral

Jérôme Gaillardet's two fetishes, the rock and the coral. Photography by the author.

3.3 In the field – outdoor labs

"You can't be a *critical zonist* if you don't come in the field." (Jérôme Gaillardet)

Although scientists work a lot most of the year in their offices, that is not where I met them for the first time. Indeed, it was in the field that I met most of them, right at the heart of the action! It was in the observatories, outside the indoor laboratories, that I first followed the practices of the scientists who introduced me to the Critical Zone, and whom the reader will come across throughout the thesis. It is therefore the specific practices of scientists that brought me into the field. Critical Zone scientists consider that every phenomenon or entity studied by one scientific discipline is related to another phenomenon or entity studied by another discipline, and that instead of practising each discipline separately in different fields, scientists should come together on the same observation field to study everything that happens in one place. CZ scientists advocate a collaborative and interdisciplinary type of research. This is why outdoor laboratories, the field, observatories, are, as we shall see, so important for CZ science. I will briefly present below the Critical Zone Observatories I visited.

The OZCAR network[51] co-lead by Jérôme Gaillardet and Isabelle Braud regroups the French observatories. The scientists working in different labs through France (depending on their institution employs them), are not dedicated to a single observatory, but they work independently on different observatories of the OZCAR network or abroad, depending on their research questions. Most often the observatory consists of a nesting of equipped watersheds, i.e. a CZO is composed of several watersheds. Fall 2020, Jérôme and his team suggest classifying and hierarchising the different CZOs in a visualisation (Fig.5) where a 'simple' watershed CZO has one branch and more complex ones are made up of several branches, like the species evolution tree. This demonstrates the organisational diversity of each CZO. The Amazon River CZO, for example, is very complex, with almost 10 embedded watersheds of various sizes, whereas the Strengbach CZO is a simple one, defined by its hydrogeographic unit.

51 https://www.ozcar-ri.org

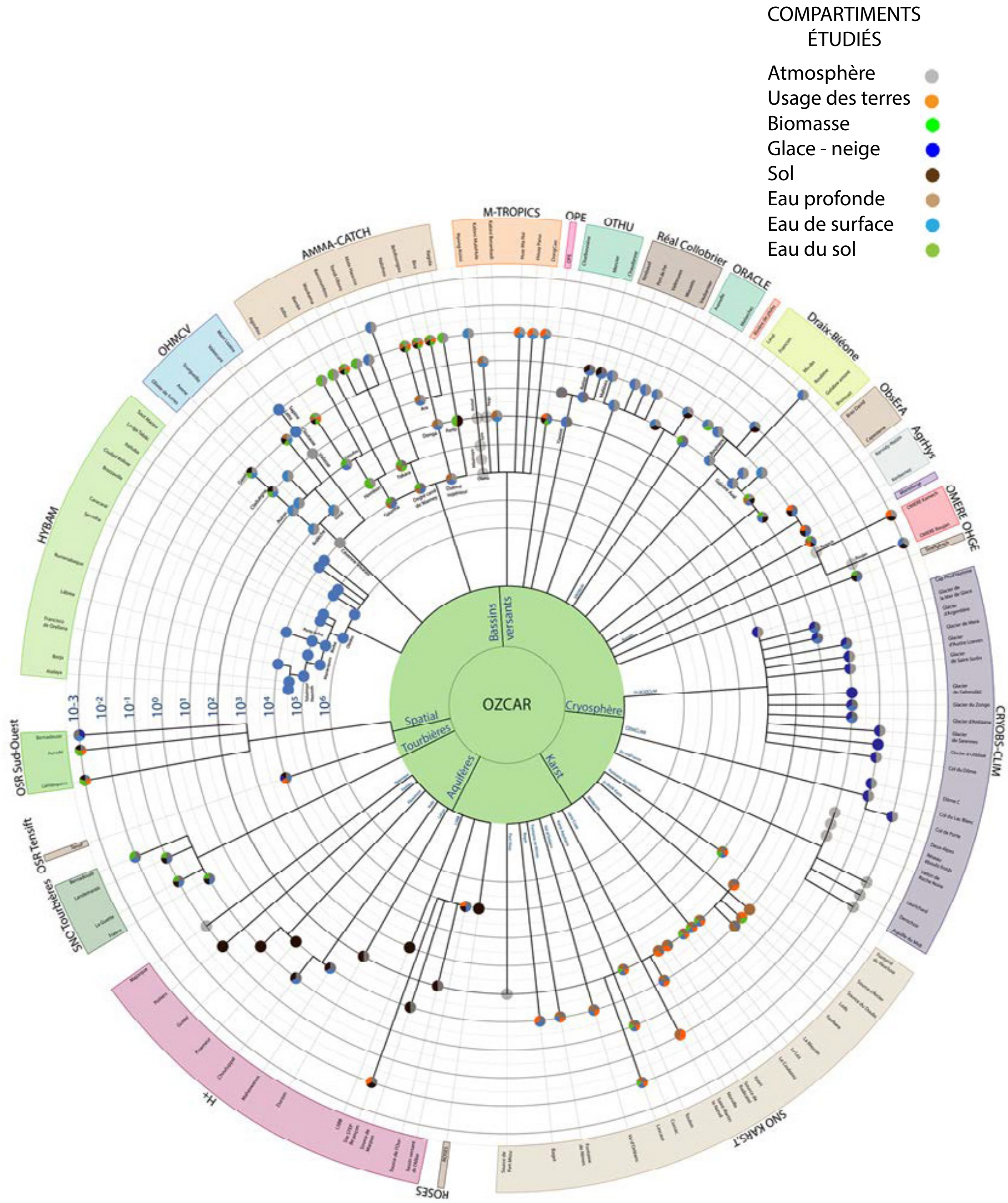


Fig.5. The 'Ozcarbre'

The OZCArbre (the OZC tree in reference to the phylogenetic tree of life). IPGP scientists are working on a representation of the French Critical Zone infrastructure. The peripheral colours represent each CZ and the branches are the nested watersheds of each CZ. This representation aims to show the spatial complexity of a CZ. Diagram published in the OZCAR Newsletter Spring 2021.

I followed the scientists in five different observatories: Orgeval, Guadeloupe, Puerto Rico, Vosges, Montpellier, over a total period of 30 days. I met nearly 50 scientists, which allowed me to observe regularities in their practices. Some scientists are not mentioned in the thesis, but they played a role in my understanding of the practices and the CZ. I have chosen to present the significant encounters in each observatory. I followed more closely about 15 scientists during long periods of fieldwork where I spent all days and nights, i.e. in the CZOs of Guadeloupe (8 days) and Puerto Rico (5 days) (French and American West Indies), the CZO of Strengbach in the Vosges forest, Eastern France (14 days), and at the CZO of Orgeval near Paris (2 days). These CZOs have different climatic gradients, sizes and landscape characteristics, and are the setting for long or short term campaigns. A campaign is either a routine operation - getting measurements every 15 days from the instruments in the field - or a short intensive field trip to collect specific measurements. I followed them during these 'campaigns', I took notes, recording the course of each day, and separately, my comments. A report was written after each CZO visit. It is important to mention that the CZOs where I carried out ethnographic observations are not case studies, as they are not exemplary of what is an observatory in general, but places where I could study the active network, trace trajectories and focus on some segments that I got to know in depth. I draw maps to situate the observatories in France and US, with their landscape **(Fig.6)**, their environmental issue **(Fig.7)** and the status of my fieldwork **(Fig.8)**. Small descriptions of each observatory can be found in the data sheet "Field-Outdoor labs" **(Fig.9)**.

Guadeloupe CZO

In May 2019, I followed the scientists on one of their exotic expeditions: to the CZO in Guadeloupe, in the French West Indies called OBSERA (Observatoire de l'eau et de l'érosion aux Antilles), managed by Eric Lajeunesse and Céline Dessert. As the scientific leader, Jérôme brought together a team of geochemists and geophysicists to explore the chemical and structural composition of the soil at depth in the rainforest on the slopes of La Soufrière volcano. Charlotte Le Traon, a PhD student, was working on this issue as part of her thesis; she was trying to build a model to understand chemical fluxes at depth: her research question was whether the particular topography of the island influences water chemistry. The teams were working together to sample and measure a small (but demanding!) watershed. Sylvain Pasquet, from Jerome's lab (whom I will introduce later), led the team of geophysicists. He was working with Jean Marçais, a scientist from the IPGP who mainly creates models but who was recruited in the field to follow the data collection process and help Sylvain to make the measurements which he will then process into numbers and constraints in his models. In addition to the team helping Charlotte answering her question, other scientists were pursuing different goals. Lin Ma is from China, a geochemist working on a small silicon device to better sample Uranium for this mission. Jennifer Druhan is from the USA with her PhD candidate Nicole Fernandez. They are part of the CZO Eel River in California. Jenny is a hydrogeochemist who joined the CZ because she was worried about deep water pollution and wanted to understand the causes. Gradually that led her to investigate other areas of the CZ and she is now a recognised scientist working on carbon processes in deep soils. She came to see how Jerome's team was sampling the river (Jerome's team is indeed known for its efficiency in the field). They learned about their methods and also helped with sample collection. To help the team in their task, Jérôme had also invited two interns from his class (geology degree). He took the time to explain the procedures, the field and the instruments to his students, which was very useful for me too. Another American scientist, Lou Derry, was following the team. He is a well-known scientist, winner of the French programme MOPGA (Make Our Planet Great Again) and working at the intersection of biogeochemistry and geomorphology, mainly in Hawaii. He is developing models with his post-doctoral fellow Jean. The campaign lasted seven days. Two days before the end, we were joined by a scientist from the Puerto Rico CZO. Bill McDowell is an American biochemist specialising in tropical regions. He came to Guadeloupe to take water samples to compare their biochemical content with those of Puerto Rico, a larger island not far from Guadeloupe. He had lived in Puerto Rico for a long time and had studied the resilience of the vegetation to hurricanes and floods. When we travelled with him to Puerto Rico, he informed us about the socio-political context and the difficulties faced by the population.

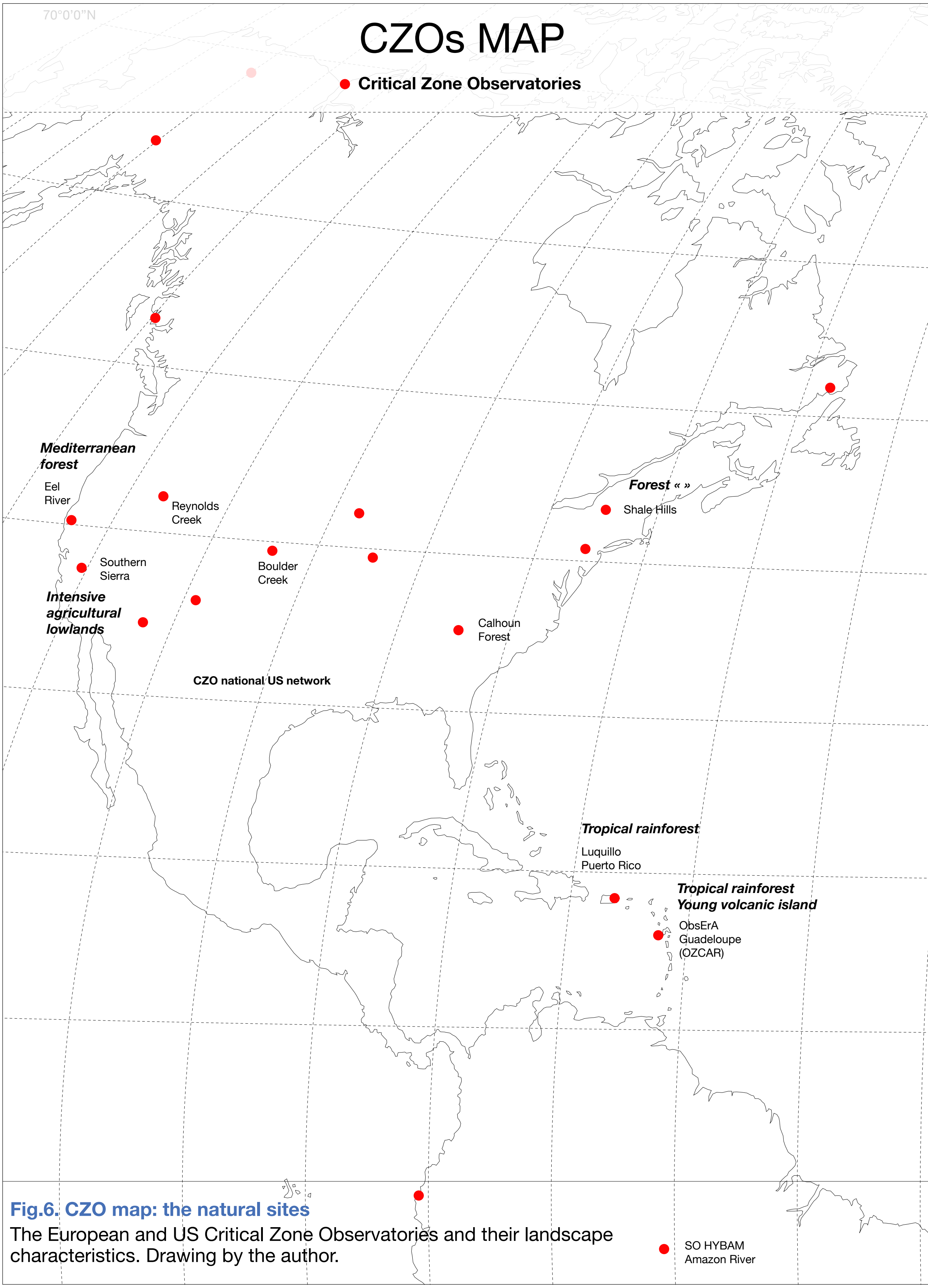
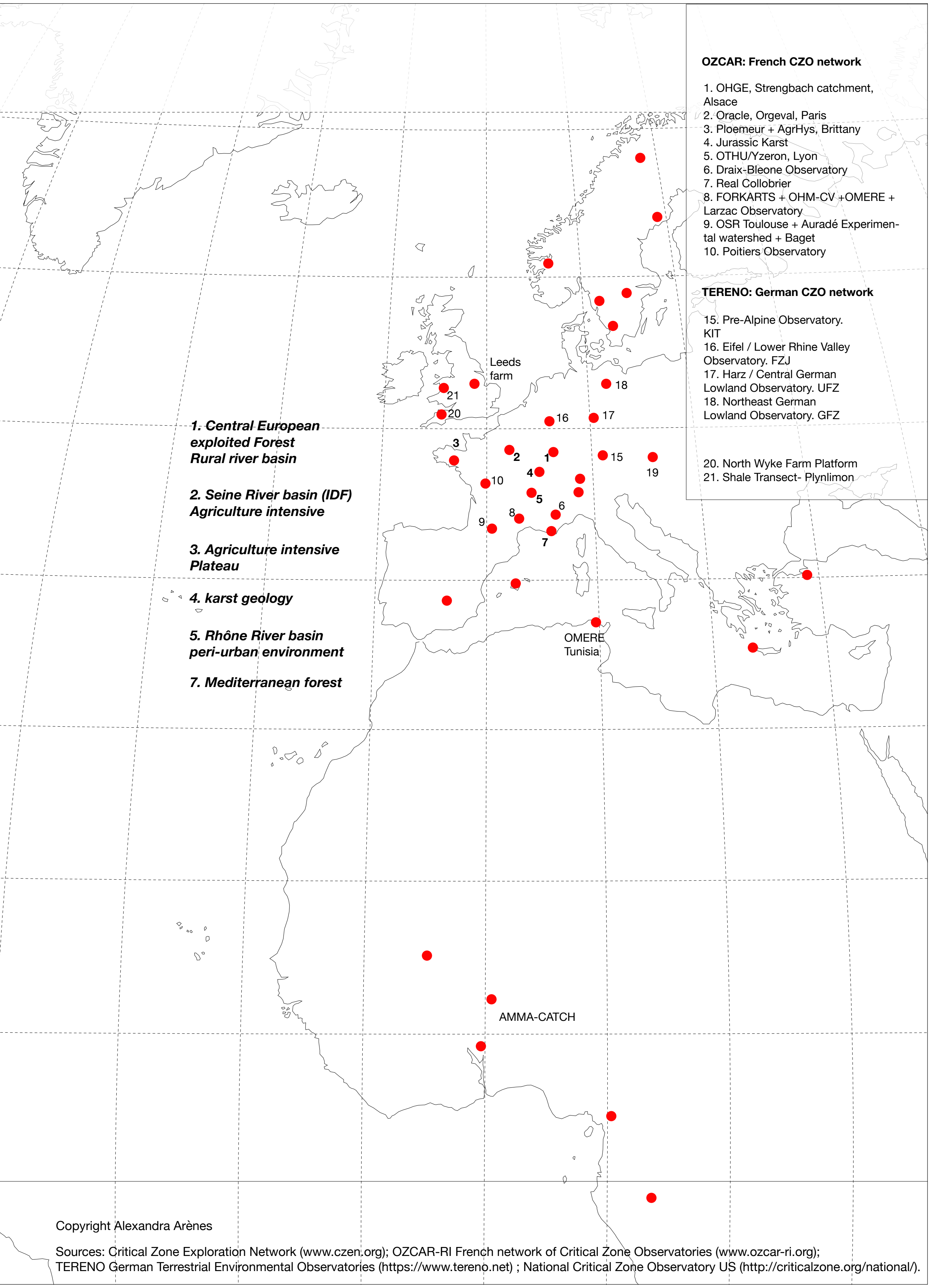


Fig.6. CZO map: the natural sites

The European and US Critical Zone Observatories and their landscape characteristics. Drawing by the author.



Sources: Critical Zone Exploration Network (www.czen.org); OZCAR-RI French network of Critical Zone Observatories (www.ozcar-ri.org); TERENO German Terrestrial Environmental Observatories (https://www.tereno.net) ; National Critical Zone Observatory US (http://criticalzone.org/national/).

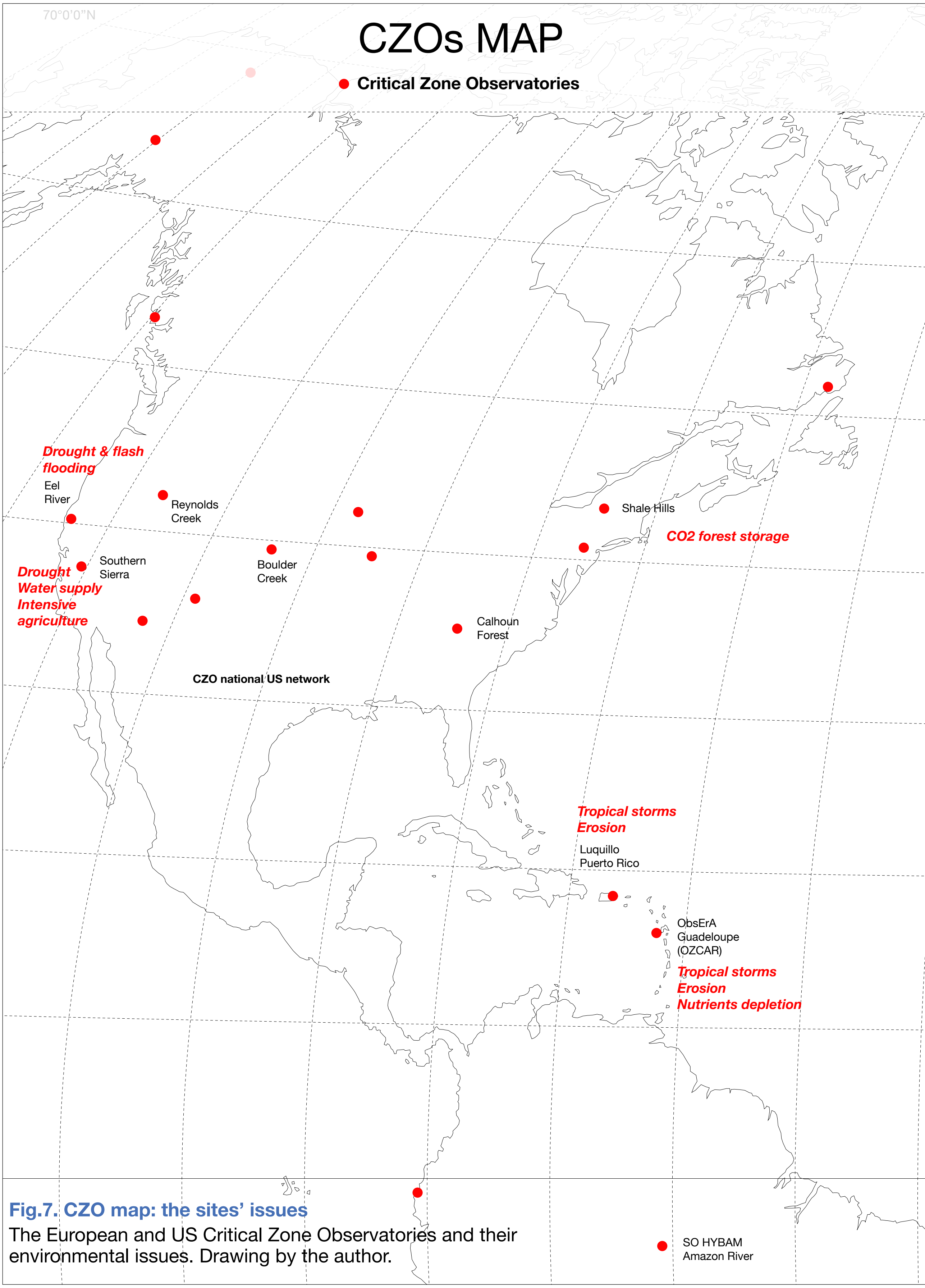
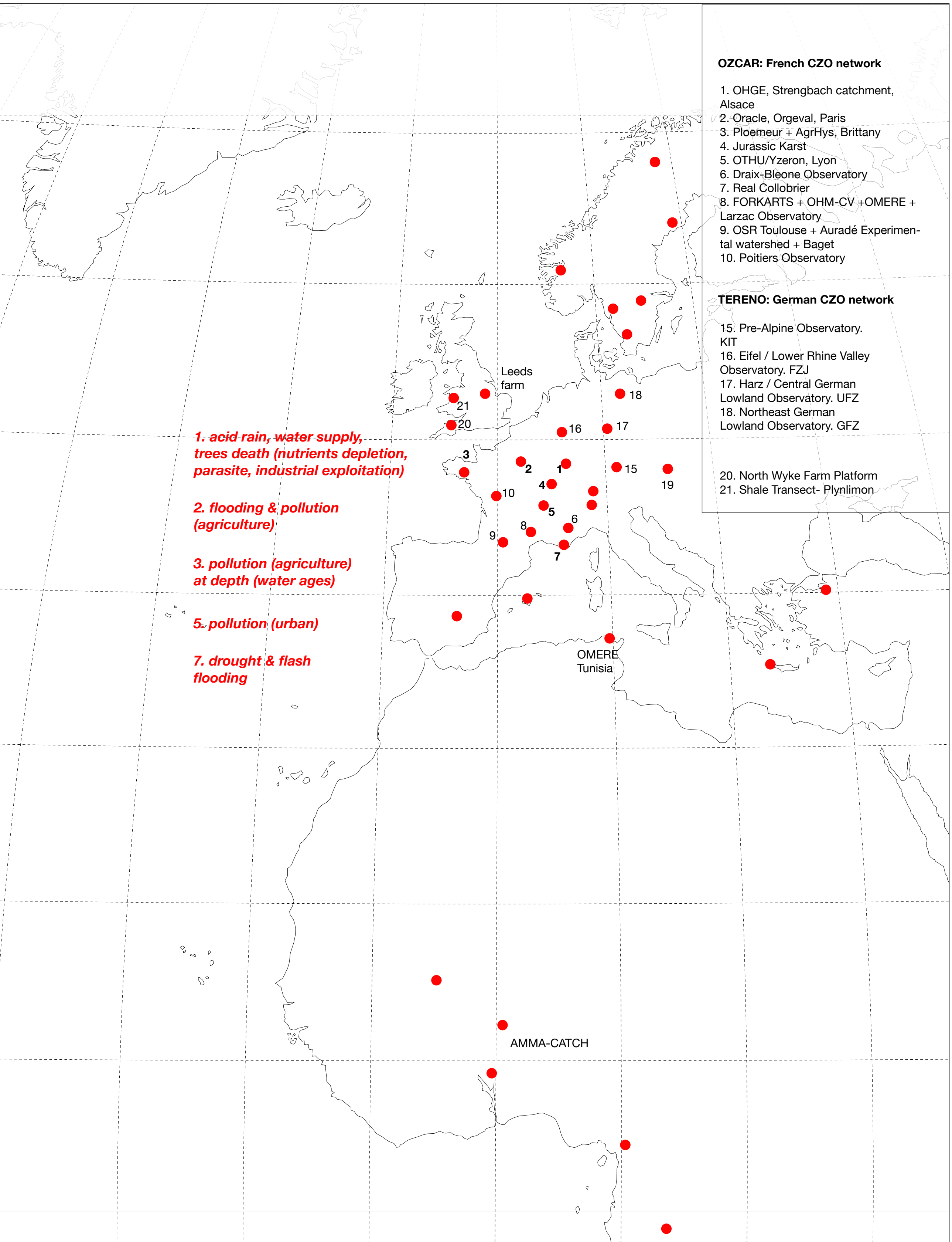


Fig.7. CZO map: the sites' issues

The European and US Critical Zone Observatories and their environmental issues. Drawing by the author.



Sources: Critical Zone Exploration Network (www.czen.org); OZCAR-RI French network of Critical Zone Observatories (www.ozcar-ri.org); TERENO German Terrestrial Environmental Observatories (https://www.tereno.net) ; National Critical Zone Observatory US (http://criticalzone.org/national/).

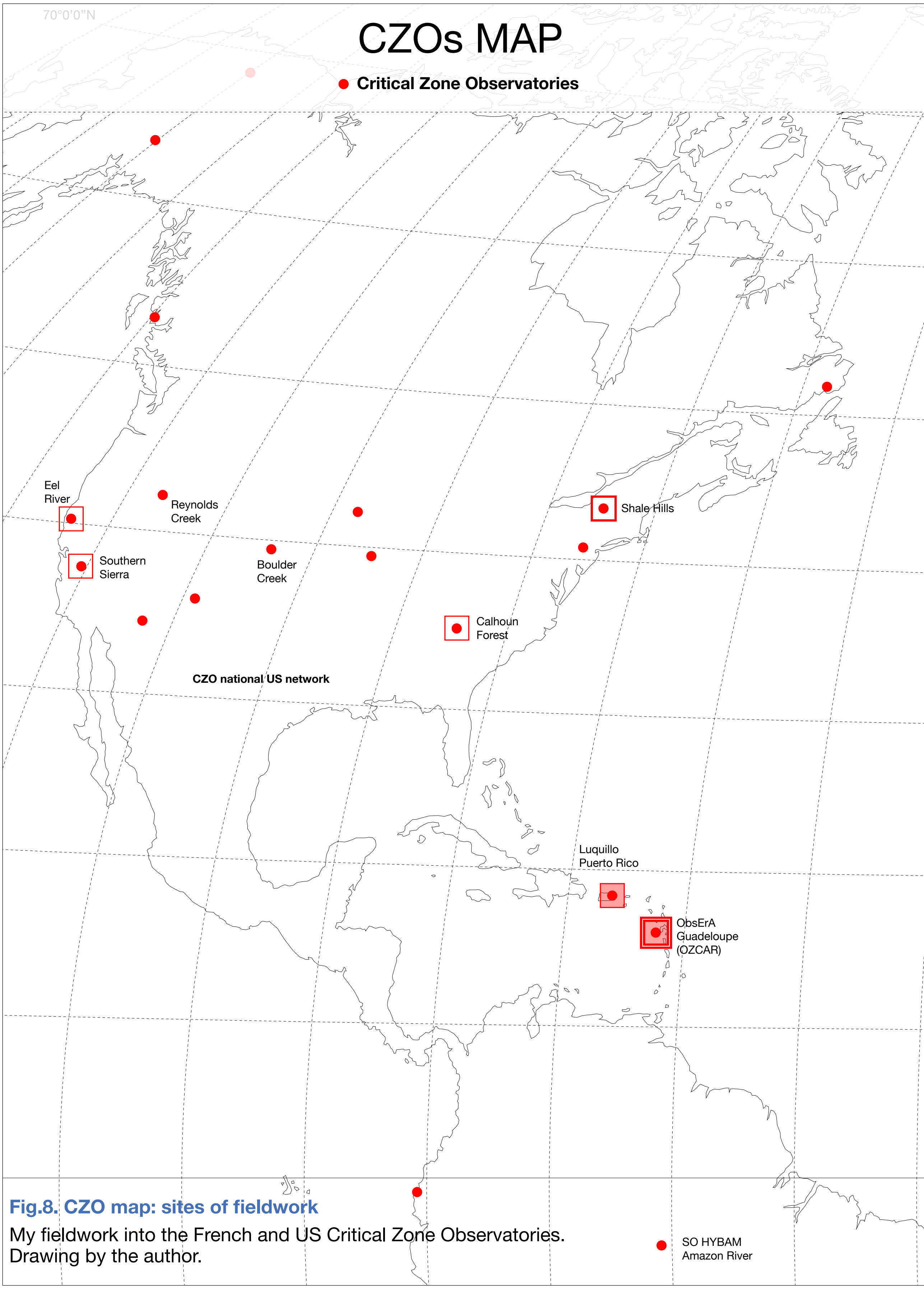
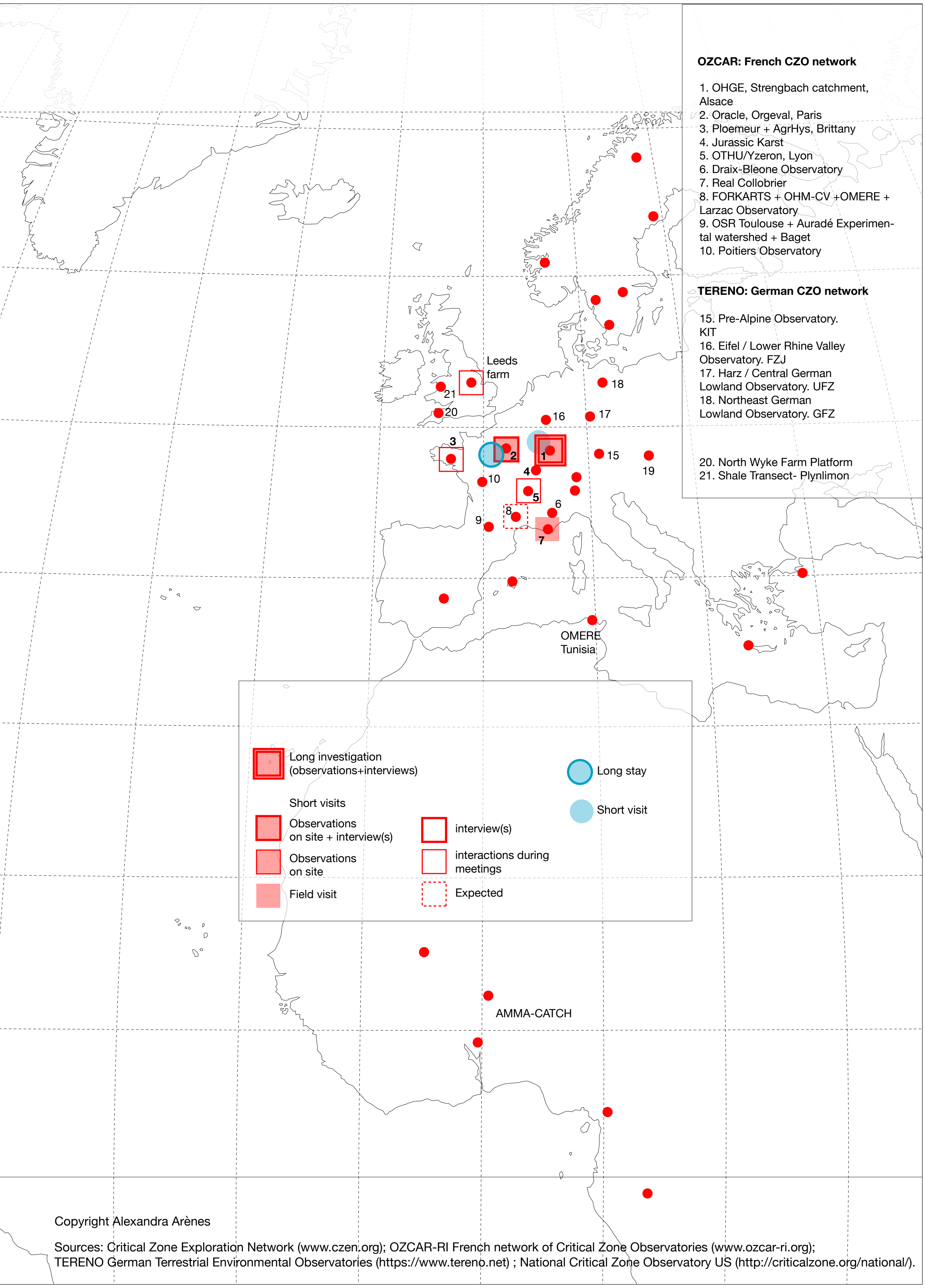


Fig.8. CZO map: sites of fieldwork

My fieldwork into the French and US Critical Zone Observatories. Drawing by the author.



Sources: Critical Zone Exploration Network (www.czen.org); OZCAR-RI French network of Critical Zone Observatories (www.ozcar-ri.org); TERENO German Terrestrial Environmental Observatories (https://www.tereno.net) ; National Critical Zone Observatory US (http://criticalzone.org/national/).

In the field – outdoor labs

CZO Guadeloupe / Rainforest, West Indies France

Location: French Antilles, Guadeloupe Island, western volcanic island («Basse-Terre»). **Team ObsErA**: Observatory of Water and Erosion in the Antilles, 2011
Geography: Young island (no big animals), volanic rocks, indigeneous tree species. Represents what can happen on the scale of the Antilles. **Surface area**: 17km^2
Issue: to study tropical zones that are particularly sensitive to environmental changes (storm and flooding).
To better understand what makes up the Critical Zone here in order to understand how forests and soils will react to climate change and what drives their responses to disturbances such as storms.
Scientific interest: Fast weathering (rocks and water). Geochemistry of waterground, rocks highly vulnerable to chemical weathering. Nutrients coming from atmopheric dust.
Instruments: flux towers, piezometers, gauge station, geophysic campaign (geoseismic with geophones).

CZO Puerto Rico / Rainforest, West Indies US

Location: US Antilles, Puerto Rico, Luquillo, northeastern mountains of the island. Palm forest. **Geography:** Older mountain than Guadeloupe. Volcanic rocks. Represents what can happen on the scale of the Antilles. Former military site, myth and stories around the forest occupation. **Surface area**: very large, 4 large watershed. Instrumented since 2009.
Issue: Storms causing salt water and clear water melting, trees destruction and dangerous landslipes.
Scientific interest: Biogeochemical processes. Resilience of the system after the 2017 hurricane Maria. Trees strategy to recover after storms. **Instruments:** gage station (stream flow), piezometers, wells, meteorological stations, canopy towrs, lysimeter nests, long-term vegetation plots. + geophysic seismic campaign

Fig.9. The places of the Observatories

Data sheet of the CZOs of the fieldwork. Photographies by the author.

CZO Orgeval / Agriculture, Temperate, Flood

Location: 70 km east of Paris at Colomiers. **Geography:** Sedimentary basin of the Seine, with different layers of limestone, marl and clay, horizontal alternance of aquifers and aquitars. Represents what can happen on the scale of the Seine. **Surface area**: about 40 km^2 (half the size of Paris). Watershed instrumented for 50 years. Monitor human activity in a basin of intensive agriculture type. **Issue:** Historically instrumented to measure the flow because of flash floods (between summer and floods, the flow can increase by a factor of 100). With the green revolution in the 60s and the IRSTEA, all the plots were regrouped, drained at 70% of the surface, because before this area was marshy.
Scientific interest: Waterground interaction with rocks minerals (calcium, sulphate, gypsium transition)
Anthropic impact, intensive agriculture, on water chemistry: use of fertilizers (potassium, nitrate, chlorine, and sodium) contributing to water degradation.
Instruments: Riverlab, piezometers, flux tour, scintillometer

CZO Strengbach / Forest, Temperate, Acid rain

Location: Eastern france near Strasbourg (German border). **Geography:** Granit and gneiss compact and fractured rocks, Vosges mountains. Black forest, 80% spruce trees (industrial), 20 % beech trees. Represents what can happen on the scale of the Central Eastern forest. **Surface area:** about 80 ha . Watershed instrumented for 35 years. Monitor acid rain and climate change. **Issue:** Historically instrumented to measure acid rain in the 70s causing trees death. The consequences are still felt and drought due to climate change are more and more frequent posing water supply issues for villages. **Scientific interest:** Waterground recharge in semi-moutain. Resilience of the system after large amount of Sulphur contribution (atmospheric deposits). Nutrients exchanges soil-water-plants. **Instruments:** riverlab, gravimeter, piezometer, borehole, complete geophysics records, diverse trees, water and soil samplings, weather station fully equipped.

Puerto Rico CZO

After the fieldwork in CZO Guadeloupe, some of us, Jerome, Jean and I, travelled to Puerto Rico to attend the annual meeting of the American CZO, which this year was hosted by CZO Puerto Rico. Jerome is part of LCZO (Luquillo CZO) steering committee and Jean was also working on a model here. During the 4 days of the meeting, we visited twice this large observatory, spreading over several sides of the mountain, we attended poster sessions where different scientists and students showed their current work, and several lectures by senior scientists. I could also attend a meeting of the board of directors of the US CZO where the restructuring of the network was discussed due to the upcoming financial cuts. During these days I met a large number of scientists including Jane K. Willenbring, an American researcher who studies soils, vegetation and chemical exchange, and Gilles Brocard, a French geomorphologist who studies the process of island formation. I had informal exchanges with many others. On the first visit to the CZO, with a small group from Bill's team, an engineer, Kayle, showed us all the equipment installed, another native scientist, Bianca, talked about the myths and folk beliefs surrounding the forest.

Orgeval CZO

I visited the Orgeval CZO near Paris in July 2020, with Jérôme and two other scientists, Sophie Guillon and Jean-Marie Mouchel, whose mission was to sample the water at several points. I was also able to visit the Riverlab with Paul Floury, a young researcher who is developing this new machine to decompose the chemistry of the river (we will learn more in the empirical chapter on River). The Orgeval CZO is an agricultural environment where fertilisers and other chemicals are applied into crops to increase productivity.

Strengbach CZO

I visited the CZO Strengbach several times because it is a typical observatory with a variety of instruments and has been for the last 30 years, and because I worked on it for an exhibition on the Critical Zone, which allowed me to go to the field more often and to gain more knowledge about it. The Strengbach CZO is located on the French-German border in the Vosges forest near the city of Strasbourg. It was established as a result of the acid rain disaster that ravaged European forests in the 1980s. An association of foresters and scientists, as well as the consul of the town of Aubure (the village where the observatory is located) worked together to establish it. Since then, the observatory has become well known and has enabled hundreds of scientific papers to be written. Marie-Claire Pierret, a geochemist from the Strasbourg laboratory (OHGE) is in charge of the observatory. She supervises the bi-weekly records and often goes to the field herself. She was my 'guide' in this CZO and introduced me to the scientists working there to answer specific research questions. In the field, I met Solenn Cotel, a research engineer who works on sediments transported by the river and Pierre, a soil scientist who studies soil resilience. I also met Paul Floury who also works on the riverlab of this CZO, and who gave me a full explanation of the machine.

<u>Adaptation of the methodology: the ethnographic field interviews</u>

Thanks to the long stay in these observatories, I was able to learn more about each instrument, to understand what the scientists do, and what knowledge is acquired. During the course of a day's work in the field, scientists record measurements at different stations. Sometimes it is just a matter of reading a graph, changing a bag and putting it back, sometimes maintenance is needed, sometimes scientists take specific samples, sometimes they install a valuable new instrument. I remained silent, taking notes and short videos or photos, as in visual STS practices enriching the fieldwork by the multiplicity of medium (Galison, 2014). But in the field, the scientists almost always talked to me spontaneously, explaining what they are doing with this or that instrument, perhaps because they are used to explain what they are doing to the students or during field visits by colleagues. As I was encouraged to talk, I asked questions about the observatory: what the general purpose or subject of the research was carried out here, and what they were doing in the field. Therefore, I had to adapt the classical methodology of ethnographic observation to what I call ethnographic field interviews, i.e. small interviews between two observations that take place directly in the field, especially to understand the use and the crucial interest of the instruments, and the knowledge they allow to obtain. With a map, the scientists often started to show me the stations, where the instruments were placed, or where we needed to go to get the measurements or to place other instruments **(Fig.10)**. This helped me to grasp the geography of the area. In this way, I was also able to understand the purpose of the instrument, what it recorded, how it was manipulated, to which research question it was related. In the field, the scientists also generally tend to comment on the first results more openly than in front of their paper in the office, where they were more cautious in presenting the results. I asked about the different stations, why they were placed there specifically, what kind of data they were collecting, and what knowledge they brought. We went mostly by foot, which allowed me to ask other general questions about the field, the main problems, to get their comments on the relations with the local communities, the problems they might have with them or with their own team organisation, or with their equipment. The ethnographic field interview is thus an adaptation of the standard walking interview. However, it is not about random explorations. I have experienced what it is like to be in the *field* versus what it is like to be in a *landscape*. For example, in the tropical forest of the West Indies, the scientists did not deviate from the planned route, and even when they were wet to the bones, worried about the arrival of a storm, they continued their measurements **(Fig.11)**. They had a mission, they were not contemplating a landscape. Indeed, scientists in the field have a procedure to follow: they do not 'wander' randomly through the forest. Ethnographic field interviews are therefore very specific interviews. The scientists take measurements, and it is these particular practices and relationships to the environment that I was given the opportunity to follow, as challenging as that can be! In this way, I was able to carefully draw the distinction between field and landscape. The fieldwork follows a pattern of visits, from one station to another, usually from upstream to downstream of the observatory's watershed, ending at the strategic point that is the river mouth. The visit actually follows the deployment of the laboratory in the field. Thus, it is not a geographical picture of the watershed. It is not a question of moving around with a map of the territory seen from above but of going from one instrumented station to another. This method of talking to the scientists while they operate the instruments offers a very concrete perspective on what the instruments make visible.

Fig.10. Fieldwork in Guadeloupe, the map

The topography map of Guadeloupe. The scientists plan their campaign field, spotting the places interesting to measure. Photography by the author.

Fig.11. Fieldwork in Guadeloupe, the river

In the field at the Guadeloupe CZO. The scientists continue the samplings despite of the storm coming. Photography by the author.

Indeed, the scientists' explanations bringing the instruments into the presence accentuates the gap between the experience of a monitored environment and the experience of an unmonitored landscape. The notion of landscape misses important elements and obscures various agents. This understanding of the environment is only possible in open-air laboratories. The scientists' gestures when handling the equipment reinforce the oral descriptions they can give of their practices: in the field they describe what they do and they perform what they describe. Scientific practices in action provide an empirical space for their description. The many entities that make up a soil, a river or the atmosphere appear there. They become a presence in their own right, not an external context 'out there'. Ethnographic field interviews allow for an understanding of geological and ecological assemblages 'inside' the Critical Zone and not 'in front of' a landscape. Scientists do not contemplate a landscape but perform manipulations to decompose the elements previously taken for granted: each instrument decomposes the landscape into numerous ingredients, flows and phenomena.

3.4 In the lab-offices

In this section, I will present the indoor places where I followed the scientists, grouped in the data sheet “In the lab-offices” **(Fig.12)**. Then, I will describe the methodology I used to understand their practices.

I spent a few months before the pandemic (January, February and early March 2020) in the IPGP laboratory in Paris to conduct more ethnographic observations and interviews, and a few weeks part-time when it reopened (from September to November 2020, about 4 months in total). The IPGP is a recent building composed of laboratories and offices with a nice rooftop cafeteria where scientists meet for lunch. The laboratories are nestled in the centre of the building, surrounded by corridors leading to offices with windows overlooking the sumptuous Jardin des Plantes in Paris’ 5th arrondissement. Whenever I walked through the corridors, I could see the scientists at work, dressed in white, through the glass laboratories. The scientists are assigned in pairs to the offices and I was lucky enough to be in one of these offices. There, I was able to interact with the team on a daily basis. Sylvain Pasquet, whom I met at the Guadeloupe CZO, is a geophysicist who studies the composition of the soil in the CZ, the part that has so far been invisible and underestimated (and under-instrumented!). Unlike most geophysicists, Sylvain does not look for resources deep in the Earth but is interested in the layers that make up the Critical Zone, from the surface to 500 metres depth at most. Paul Floury is a geochemist who developed the Riverlab, a machine that decomposes the chemistry of a river at a rate never before seen. Fully trained with the CZ, his research is deeply influenced by this paradigm. Julien Bouchez is a geochemist specialising in river sediments and how they shape the Earth. I interviewed these three researchers, as well as Jérome Gaillardet on four occasions at different stages of my fieldwork. I talked to other members of the lab team and get a general idea of the diversity of the laboratory’s research in their questions and sites of investigation. Some of them work on the volcanoes of Reunion Island (Eric Gayer), others on the great rivers of China, others on the nearby Seine basin (Pascale Louvet). All of them work with other scientists from different laboratories around the world.

In the lab-offices

Laboratories

IPGP lab Paris

Location:
1, Rue Jussieu, 7005 Paris.
Institution since 1854. New building 1999. 500 people, 16 research teams (Earth and planetary interiors, Natural hazards, Earth system science and Origins.)
The Critical Zone team, part of OZCAR team, is in the «External envelopes geochemistry» at the 5th floor.
Resources:
Around 10 scientists working in the team + postdoc and doctorants (5 students)
Instruments: spectometers, white chemical rooms
Rooms: 7 offices shared by 2 persons.
Activities:
«the geological consequences of the Earth's water cycle.»
Geochemical measurements, result processing, funding files, papers, group discussions, team meeting every week.
Scientists met: Jérôme Gaillardet, Sylvain Pasquet, Sylvain Kuppel, Eric Gayer, Paul Floury, Julien.

OHGE lab Strasbourg

Location:
EOST, 1 rue Blessig, 67000 Strasbourg.
Institution since 1830-1918
Research team: LHyGeS - Experimental site (the CZO) is named OHGE
Resources:
People: 13 scientists + post-doc and PhD.
Instruments: white lab rooms, spectometer chamber
Activities:
Analysis and the understanding of hydrological and geochemical phenomenon in natural environments. Data coming from the Observatory is analysed and stored here. Regular activities of a lab: Geochemical measurements, result processing, funding files, papers, group discussions.
Scientists met: Marie-Claire Pierret, Nolwenn Lespages, Solenn Cotel, Anne-Désirée Schmidt, Pierre, Colin

Fig.12. The places of the laboratories

Data sheet of the indoor places of the fieldwork. Photographies by the author.

Events

AGU event, San Francisco

Location: Moscovitch center San Francisco. AGU stands for American Geophysics Union, regrouping all Earth sciences, including NASA. Gathering of 10000 scientists from 9 to 13 December 2019. **Topic:** The Critical Zone scientists were scattered in the different thematics (hydrology, atmosphere, geochemstry, biocehmistry, etc) as the CZ ranges from a diversity of disciplines. A special session was nevertheless organised by Jérôme Gaillardet and Anne K. on the possible links between social sciences and natural sciences in the Critical Zone. I have been invited to present my research in a 8 min talk along with Anna Tsing, Lesly Green and Susan Brantley. **Program:** Talks, poster sessions. I floowed both US and French Critical Zone scientists. https://www.ozcar-ri.org/fr/agu-washington-d-c-10-14-decembre-2018/

OZCAR days South France

Location: Sète, seminar rooms, and site visit of CZO Larzac. 10/11/12.03.2020
Topic: Annual meeting about the advances in Critical Zones Sciences.
Presentations of some researchers, results and outcomes, new funding.
Structuration of the network.
With: Most of the scientists of the French network OZCAR (around 100 people) + invited scientists from other countries or researchers not belonging to the network. https://www.ozcar-ri.org/fr/4eme-journees-annuelles-ozcar-10-12-mars-2020-sete/

CZO Larzac / Karst, Mediterranean, Drought

Location: Larzac Plateau and Lez Aquifer, South center France. **Geography:** Karst geology (caves). Mediterranean vegetation. Observatoire GEK Géodésie en Environnement Karstique), site de la Jasse, Hospitalet-du-Larzac. Represents what can happen in karstic regions over the world. **Surface area:** about 100 km^2 Monitor groundwater recharge and weathering. Visit of the caves + Visit of the water supply station pumping water at dept. **Issue:** Mediterranean regions suffer from more and more severe drought, and the population is increasing. Extreme hydrological event: flash and torrential flood. **Scientific interest:** How water circulate in karts, caves, grounds? How to measure at these depths? **Instruments:** gravimeters, flux towers, piezometers, gauge station, sismology.

The OHGE is the laboratory linked to the CZO Strengbach and it is located in Strasbourg, a city at the French-German border. Most of the scientists I met in the field work there. I was able to observe laboratory practices with Anne-Désirée Schmitt, a biochemist whom I followed into the white room for a routine operation of decomposing leaves to analyse their chemical composition. I interviewed Marie-Claire Pierret, and two geophysicists, Jacques Hinderer and Nolween Lespages. Nolween creates models to study water paths and Jacques, a senior scientist, studies the amount of groundwater under the mountain that sustains the village nearby.

I also attended several important scientific meetings: the AGU in December 2019, seminars at IPGP in November 2019, OZCAR days in March 2020 and webinars at IPGP every Friday in autumn 2020 until summer 2021. I followed the IPGP lab to the AGU scientific conference in San Francisco in December 2019. The AGU (the American Geophysical Union) is a large meeting of all earth sciences (including NASA!) gathering 20,000 scientists from all over the world for one week. Among all the posters and conferences available, I followed the sessions identified as 'CZ science', thanks to Virginie Entringer, communication manager of the OZCAR at the IPGP who had drawn up the list of them. I was able to follow several presentations by scientists I had already met: Eric Gayer from IPGP, Jennifer Druhan, and many others whose research focuses on soil, carbon, rivers, geomorphology, agriculture, roots, etc. The CZ sessions were in fact very diverse and heterogeneous! I also presented a paper in a special CZ session on social and natural sciences, organised by Jérôme Gaillardet and Anna Krzywoszynska, a British sociologist (The University of Sheffield) working on agricultural soils and founder of the Soil Care Network. She also works with a CZ scientist, Steven Banwart, head of the UK CZ network, whom I had met quickly at a conference at the University of Leeds, during my first year in Manchester. At this session at the AGU, I presented my work in progress on visual representations of the CZ. Anna Tsing and Lesly Green were also presenting papers. Jerome had invited Tsing to discuss with American scientists the possibility of cross-fertilisation of social science research with CZ research in some observatories. Susan Brantley, a geochemist and initiator of the Critical Zones concept in the US, also presented a paper in this session. Overall, the AGU event was rich in experience and exchange. It allowed me to connect with the wider CZ network and exchange ideas on the CZ concept. My trip was funded by OZCAR because of my participation in the social science session. The second event took place just before the lockdown, in March 2020. This was the annual OZCAR meeting where the French scientists of the network meet to exchange their results and upcoming research questions. The event takes place over 3 days, with many presentations of the work and a visit day to the observatory hosting the event. This year it was in the south of France, near Montpellier, at the Larzac CZO. This CZO studies water resources, a major issue in this part of France in a karst environment, characterised by a deep soil composed of caves and cavities, forming a particular landscape on the surface and a complex network of water infiltration below. This CZO includes weather station instruments and sophisticated gravimeters to probe the depths. We also visited the drinking water plant which illustrates the close collaboration between these scientists and the public services. During the lectures, I met Sylvain Kuppel, a scientist modeler from Lyon, whom I later interviewed virtually. The event offered me the opportunity to get in touch with many scientists and learn about their research and observatories, as well as to visit another CZO, and although the trip was quick, it helped to improve my general understanding of the CZ and its issues. Depending on the type of scientific activities, I was able to observe them closely or not. Those taking place in the field were possible. But I was not able to fully follow other practices, such as those in the laboratory, which were restricted by the pandemic, and therefore access could not be provided. However, I have relied on different sources: virtual interviews as well as secondary sources such as virtual seminars and scientific articles. This explains the different nature of the data and therefore the differences between some empirical chapters. The context of offices or laboratories premisses enable longer interactions, and so this is where I conducted semi-structured interviews with some scientists. Semi-structured individual interviews follow a question and answer format for approximately one to two hours. The scientists talked about their activities, but not performing them. This methodology is therefore based on the scientists' discourses. This data is composed of 16 semi-structured interviews (12 scientists, 4 interviews with the same person), conducted at different laboratories or places where we stayed after field observatories (see table of interviews in annex). Their duration ranges from 40min to 180min. I interviewed the members of the various disciplines composing the CZ science: geochemists, geophysicists, hydrologists, biochemist, modelers. How to ask the right questions? This is the first concern when writing the questionnaire. My advantage was that I had already been in the field a few times. I noticed that the instrument engages the scientists in a pragmatic discourse and pushes them to explain in simple terms the processes it makes visible. Indeed, they use a very specific language to talk about their work in the field: measuring, decomposing, sampling, etc., showing the pragmatic context of their actions, what it means to measure all these elements in the CZ. This is a typical ANT interest: an interest in the pragmatic course of actions, not just in the scientists' speeches. This is why, during the interviews, I first questioned them about their practices, focusing on their field experiences: how they describe them, what is a typical day between the field and the laboratory, where they work, what they are interested in, what instruments or procedures they use in the field, what results they obtain on each specific site they work on, what elements they trace, what insights they have into the particular composition of the CZ, how they obtain and process data, and then how they rely on the whole network to validate and disseminate their research (see interview guide in annex). In this way, I was often able to obtain interesting field anecdotes, a description that reveals aspects of the CZ. Then I directed the conversation towards more delicate subjects: whether they were aware that their research contributed to the CZ approach and if so in what way, by asking them which processes they were studying, how these interacted with other processes and which aspect of CZ was thus made visible. During the interview, if the scientists were too technical, I would ask them to remind me what their research was for, what was at stake and how it was useful for society. It brought the interview back to unsuspected or unexpected aspects that were revealed through the progression of the questions. Conversely, each time the interview moved towards general assertions, I went back over their practices. The scientists interviewed were at different stages of their careers. I interviewed a CNRS silver medalist, some post-docs, a PhD student, an entrepreneurial scientist and other scientists in various positions, as different organisations recruit them. Some of them have changed their practices (and careers!) to answer CZ questions, while others, the younger ones, are directly trained in the CZ paradigm. But most geoscientists are primarily trained to study the depths of the Earth to work in resources extraction companies. The study of CZ is perceived as 'surfacing', often laughed at by colleagues. Yet it is described by scientists as a real choice, a commitment they have made, often after a rude 'awakening'. For example, Jacques, who already has a long career behind him in gravimetry, started by studying global dynamics, the liquid earth core, problems related to earth deformation and rotation, and earth tides, which are rather theoretical studies. But then he was confronted with increasing demands to monitor water reservoirs. He now works on hydrological issues in France, Iran and Africa, as these are major ecological and social issues. During the interviews, the scientists often showed me pictures, the results of their research, and I also asked them to show me their software and graphics in progress (see last question of the interview guide). The scientists use visuals with four aims: to grasp, scheme, conceptualise their object of study; to enter data measurements, to calculate; to share their findings to collaborators; to disseminate their findings (Latour, 1986; Lynch and Woolgar 1990). During the interviews, the role of biogeochemical cycles in the CZ came up several times. My aim was to better understand the crucial role of biogeochemical cycles and the processes that the scientists kept mentioning to me, but which I could not fully understand. I thus started to propose a method for them to draw these cycles with me based on a template I had created for the occasion **(Fig.13)**. The model, or template, is a kind of map with an alternative projection to visualise the cycles of the Critical Zone, that I will describe in the chapter 7 "Mapping the Critical Zone" of this dissertation. I brought it with me to each interview. It is a semi-drawn diagram where only a few structuring lines are placed. The scientists were invited to draw the cycles of their observatory using this specific structure, which was open enough to be adapted to any observatory and any question. The aim was to get scientists to draw the cycles of the CZ. However, this model was not used for every interview, as this is more time consuming and experimental. I was able to go through with Jérome Gaillardet, Marie-Claire Pierret and Paul Floury. I was only able to establish coherent cartographic projections with Jérôme and Marie-Claire. I will describe this work and the alternative projection to visualise the specificities of the CZ that it provides in chapter 7 of the thesis.

3.5 Conclusion: ethnographic observations to study landscapes

By tracing the activities of scientists indoors or outdoors through ethnographic observations or interviews, I was able to establish the continuities between the laboratories and the field, to understand what scientists do in both cases, what knowledge is created, transferred and how practices change according to the situations in the field or in the laboratories. The practices of scientists can sometimes seem difficult to understand. A scientist may start by studying rock or deep soil, and ends up studying water or the atmosphere. The CZ paradigm means that disciplines intersect in one place. Scientists exchange hypotheses and data, and some scientists also change their own practices. It is therefore difficult to disentangle which part of the CZ is being studied. Is it the soil, the tree, the river, the whole water cycle, just a particular chemical element? For the purposes of this thesis and because my main question is to understand how the understanding of landscapes is changed by the CZ, I have chosen to untangle these practices and re-situate them in a more 'conventional' repertoire. This is so that the reader can understand the movement through which the soil, river and atmosphere become something else through CZ practices. Therefore, the presentation of the empirical data develops a specific scenography to address these questions: what knowledge can we extract from the earth sciences of the Critical Zone? How does the Critical Zone requalify spaces, deconstructing scales? How do the practices of the scientists reveal invisible geographies? What connections are re-established? How might this improve architectural design in the disorienting Anthropocene era, and make it more attuned to the needs of the New Climate Regime and more climate responsible? How does this address the lack of understanding of the cosmopolitical / Gaia in the field of design / visualisation?

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OBSERVATORY LOCATION

....

ISSUES

....

CHEMICAL ELEMENT

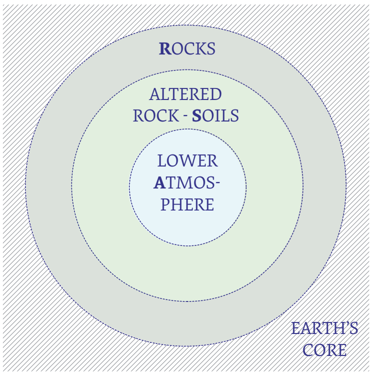
....

STEP 1: DEPTH

RESERVOIRS

Circle thickness = stocks, reservoirs

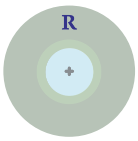
5000	Reservoirs: stocks in units of measurement used for each cycle



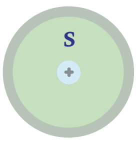
R = rocks (rigid envelope)

S = superficial soils (solid but loosened and hydrated envelope (soils and alteration covers) > altered area

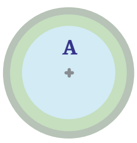
A = Atmosphere, low (gaseous envelope atmosphere)



larger quantity in the rock layer



larger quantity in topsoil layer



larger quantity the atmosphere layer

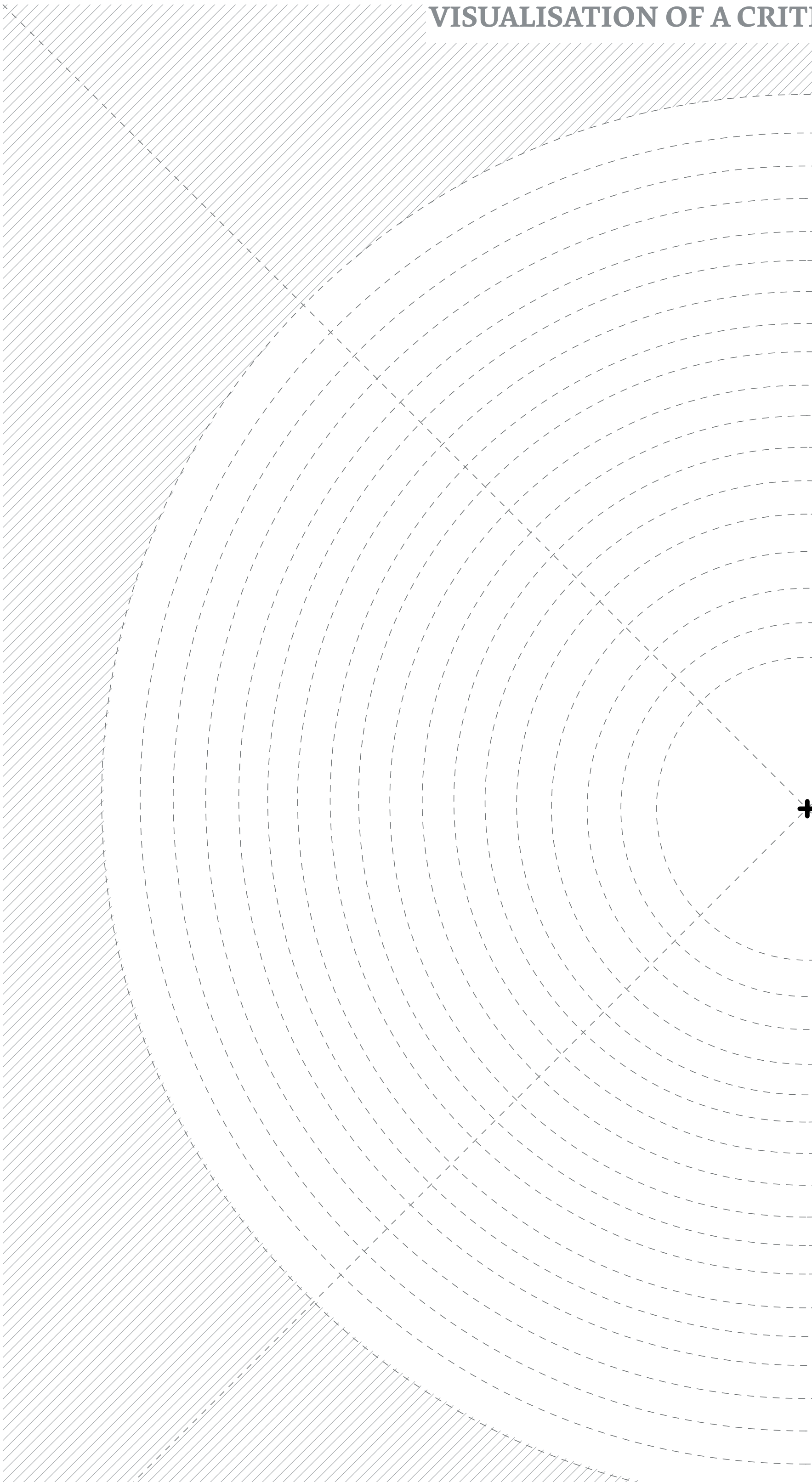
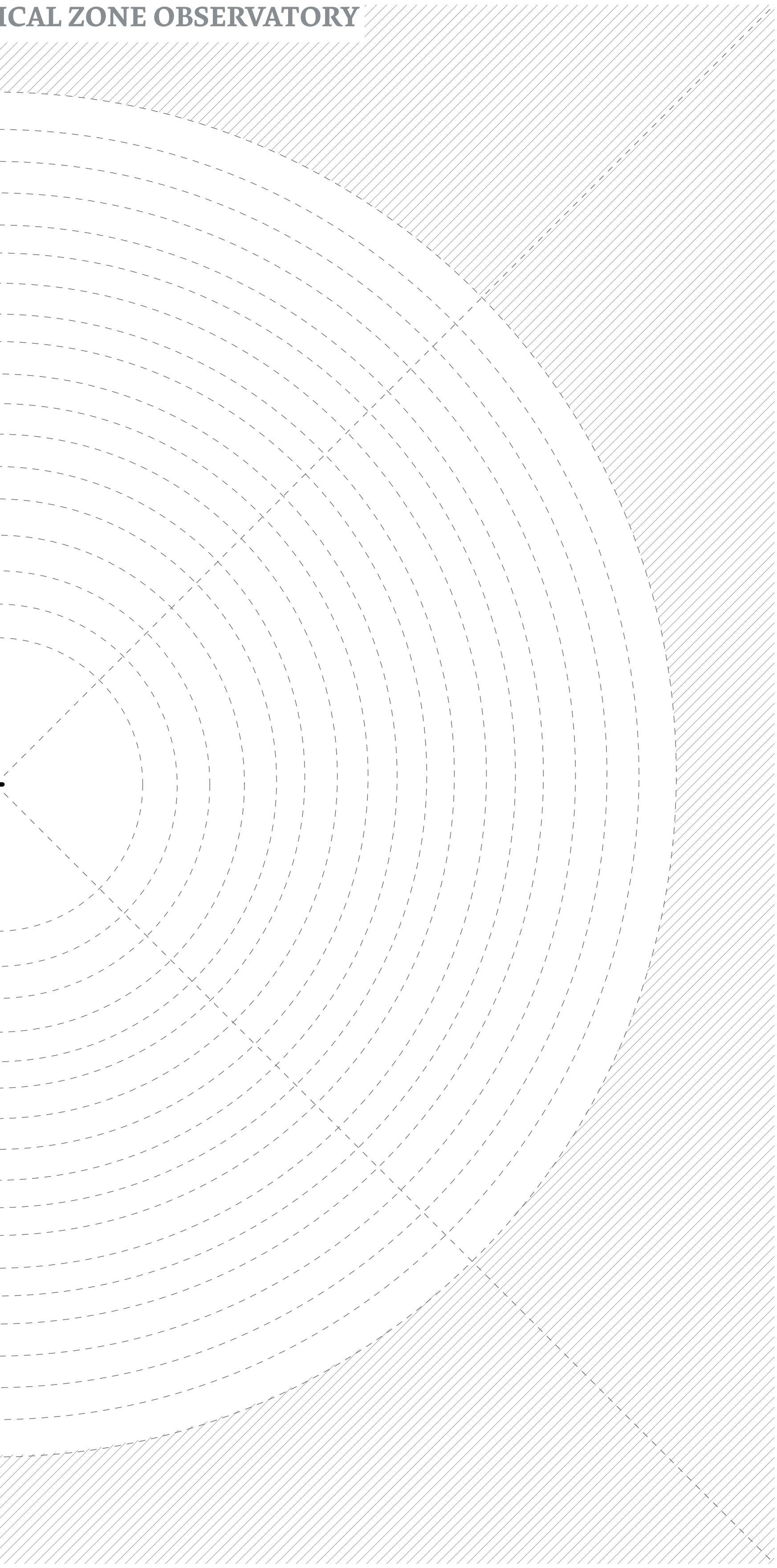


Fig.13. The drawing template

Brought in some interviews to draw biogeochemicals cycles with the scientsts. Drawing by the author

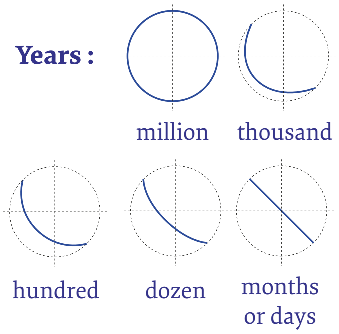


STEP 2: TIME, CYCLES

RESIDENCE TIME SPIRALS

Time scale of spiral bifurcations (flow)> Flow speed from one reservoir to another

Years :

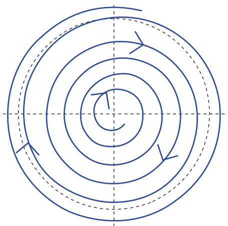


FLOWS

flow quantity

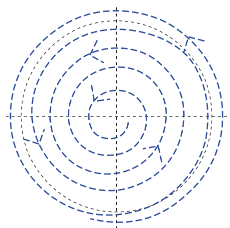
spiral arcs thickness

flow ways



from center
to periphery

⟶ **Centrifugal**



from periphery
to center

⇠ **Centripetal**

Statement on the empirical chapters

The three empirical chapters that follow are organised around three main landscape entities: *soil, river* and *atmosphere*. These entities are indeed the ones that architects or landscape designers deal with in a project, but they are also the entities involved in the short definition of the Critical Zone: an area on the Earth's surface that extends from deep rock (soil) to the lower atmosphere and where water percolates and spreads life. In each empirical chapter, the practices of the scientists were carefully recorded and analysed. It appears that four practices or movements are recurrent and common to all situations in the CZOs, both in the outdoor and indoor laboratories (field and office). These are *observing, decomposing, tracing* and *connecting*. These movements allow us to understand how the soil, the river or the atmosphere differ, in the Critical Zone, from the anthropocentric view. These practices establish a new consistency of the natural world, which then may need to be given meaning in architectural practices. The chapter on maps, after the three empirical chapters, is dedicated to this objective: how can we visualise these new elements of nature for architectural design? This is the graphic capture of the Critical Zone, the gaia-graphy, which aims to renew architectural language.

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4 Soil

4.1 Introduction

The usual understanding of soil is that it is a surface that supports life. Soil is the surface of the Earth, and the foundation of architecture. It is known as stable, solid, compact, but also opaque, dense, dark. Overall, it is, as its name suggests, a *background* that supports activities. However, its existence is threatened: the fertile subtracts for food are decreasing, as well as its storage capacity of CO_2, water and nutrients, because of pollutions, landslides, and other soil removals. Here we will follow what a soil is and how scientists trace the complexity of this natural entity, which is usually traced as a surface on geographic maps. We will see what the soil is when we follow the work of the scientists. In the following parts of the chapter, I will re-enact this journey into the overlayered structures of the soil that the scientists observe, going deeper into the soil while moving through different topics at different speeds and from place to place. The chapter features the four practices of the scientists which allow them to define the soil differently, as summarised in the diagram on the right. The chapter follows these practices from one observatory to another, mixing my surprises in field notes (in italics) when in the field, and the scientific knowledge I learnt from them.

The first part 'Observing' underlines the difficulty of directly observing the soil, of exploring the space that is physically inaccessible because it is located below the surface. Scientists are therefore developing observation strategies, consisting in adapting instruments to explore the 'near-depth'. The second part 'Decomposing' explores the various soil properties that we would not have been able to apprehend without the scientists' observations. Soil appears granular, fractured, porous, etc. This brings us to the third part 'Tracing' which aims to understand how the scientists follow the soil components despite their evanescence. This part raises crucial questions about soil substance and its subsistence. Finally, in the last part, 'Connecting', we convey the understanding of the soil that results from these practices: the near-depth and the subterranean connections.

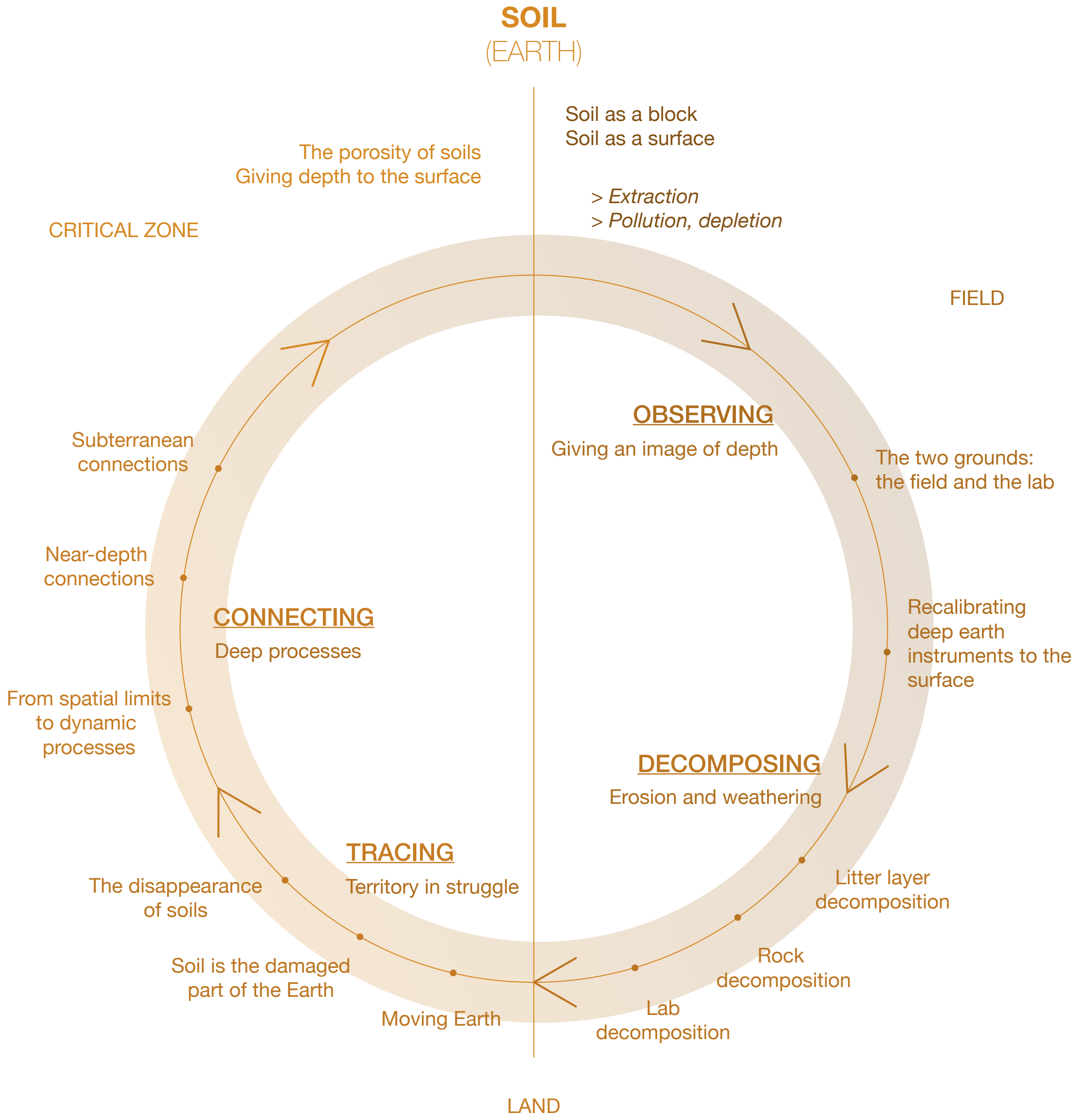

Diagram 3. Chapter SOIL

4.2 Observing: giving an image of depth

In this first part, we will follow the scientists' movements back and forth between the two places where they study the soil: the field and the laboratory. In the field, the soil is invisible but must not be reached by intrusive and destructive techniques (in contrast to traditional geology techniques using dynamite), so scientists often adapt their own equipment by hijacking instruments that are primarily designed to examine the earth at great depths.

The Critical Zone scientists question the laboratory and its hegemony over field science. In a famous article[52], Sue Brantley, an American geochemist, lists the reasons why scientists should once again study the Earth directly in the field, highlighting the 'distance' between what happens inside the beaker and what happens outside. Phenomena observed in the field occur with a difference of three orders of magnitude, that is one hundred times slower than those observed in the laboratory! It is perhaps because many agents interact in the field, a complexity that the lab cannot reproduce. The concept of Critical Zone is an approach to reduce this gap between indoor and outdoor measurements. For the CZ scientists, science starts from the field. In the observatories where I followed the scientists, routine measurements are common practice. This is the continuous aspect of the work. The aim is to monitor the behaviour of the environment through periodic measurements, and to understand its reactions over the long-term. At the CZO Strengbach in the Vosges forest, scientists of the OHGE lab (Observatoire hydro-géochimique de l'environnement) carry out bi-monthly instrument readings at the observatory's nine stations. The scientific team is divided into two groups. One stays downstream at the mouth of the river and the other climbs to the summit, 850 metres higher, first to the meteorological station, then to the tree plots and springs. I follow the group to the top. **(Fig.14)**

52 Brantley SL, Goldhaber MB and Ragnarsdottir KV (2007) "Crossing disciplines and scales to understand the critical zone". *Elements* 3: 307–314.

Fig.14. Taking ice samples

The weather station at the CZO in Strengbach. In winter, the scientists collect the water that has formed into an ice block instead, in order to record the amount of precipitation over 15 days. Video still Sonia Levy.

Fieldnotes from the Strengbach Critical Zone Observatory, Vosges forest, France, March 2020

It is winter, the mission takes longer, the scientists are moving slowly in the snow. What kind of samples they might take from this frozen and dormant landscape? They want to sample water but instead of liquid water, there are blocks of ice in the bags. They weigh more than 6 kg. In order to take the water for chemical analysis, they first have to melt the ice in a heated cabin. Then, from buckets in the ground, they take soil water solution. Here the water is not frozen because the soil is like a warm organism.

Depending on the depth of the sampling in the soil, the colour of the water changes from clear to brown. Of the litres in the buckets, Marie-Claire Pierret and Pierre only keep small bottles of each. I observe these repetitive movements: weighing the water bag, filling the bucket with water, sterilizing the bottle with this water several times, filling at least one bottle and throwing the rest of the water on the snow (Fig.15).

Fig.15. Collating soil solutions
The soil/spruce station at the Strengbach CZO. Scientists collect a brown soil solution (water that has been passed through the soil, in order to analyse its composition). Video still Sonia Levy.

This is then brought to the lab to analyse the chemistry of the water that has passed through the different layers of the soil and is therefore charged with chemical elements (nutrients or sulphur). In the lab, in city of Strasbourg, Solenn Cottel and Anne-Désirée Schmitt perform other repetitive moves which rhythm the day, as mirroring the field: filtering the water, storing the filters, running the centrifuge, operating the mass spectrometer machine to separate the chemical elements and quantifying them. In CZ sciences, long stays and regular trips in the field are important. However, as Marie-Claire Pierret (geochemist and head of the Strengbach CZO) explains, the laboratory is still essential and makes it possible to achieve something impossible with the resources of the field alone. The laboratory provides scientists with a special expertise. CZ science encompasses more disciplines traditionally attached to the laboratory such as chemistry. Thus, the laboratory provides scientists with detailed descriptions, differentiations between processes that they would not be able to differentiate only in the field. They collect soil from the field, make it react at short intervals and then over longer periods of time and thus analyse its evolution. Reducing the field-lab gap requires a restructuring of the scientific reference chains (how the data is collected, analysed and evaluated, how scientific facts are produced). This involves several back-and-forth exchanges between the laboratory and the field. It is not only the studied processes that are slower, but also the practices of scientific knowledge production due to observations in the field. At a time when researchers have to speed up, CZ science says otherwise: to study climate change, rapid disturbances, scientists need to slow down, to spend time to describe what is happening in the long-term, and so to monitor the environment on a daily basis to better understand Earth's rhythms. Thus, scientific "discoveries" are not one and for once but evolve throughout monitoring.

However, going back to the field to study it directly has drawbacks, especially to study the soil for which the scientists can rarely observe directly. As they explain, they are 'blind' to these depths, to what lays beneath our feet. The surface is easier to understand. Scientists have a very precise tracing of the topography, of its slightest relief, which allows them to draw the trajectories of the water and its speed. But at depth, the Critical Zone is much more complicated, notably because what exactly is depth and soil is controversial. Indeed, the depth of the soil varies according to the discipline examining it. Pedologists observe the first three metres, whereas geologists study it at thousands of metres depth. The CZ is in the middle, it studies the soil to the extent that water modifies it, crosses it, alters it. To do this, there are not many samplings or instruments to 'see' the soil at these depths. As Jenny Druhan (American hydrogeochemist from Eel River CZO in California) explains, it is easy to take soil and vegetation samples at and near the surface, as deep as it is possible to dig by hand, and it is also easy to dig a well and extract water from an aquifer with a big machine, but the real problem is to take the soil from the middle, neither in the very deepest depths nor at the surface: “there is a big gap between these two places, in these weathering profiles, where it is too deep to reach by hand”[53]. This ‘in-between’ depth soil or as they call it ‘near depth’ is also more difficult to sample than the great depths. The inefficiency of traditional instruments and methods leads scientists to invent new techniques to explore this intermediate zone, which is both impossible to reach by hand and to explore with instruments designed for deeper levels, so they create new instruments. Jenny’s team design a special instrument: a piece of porous ceramic that can let a fluid through, in order to bring the water above the water table, in this almost unreachable depth, to the surface to analyse its chemical content. These small devices go down to 18 metres, allowing her team to reconstruct the complete soil profiles. Another approach is to use geophysics techniques to reconstitute the porosity of soil at depth. Scientists carry out transects using geoseismic techniques to detect the permeability to water and therefore the capacity for soil formation. But like Jenny’s ceramics invention, geophysics need to be quite spectacularly recalibrated. Sylvain Pasquet, who is in charge of geophysics in the Paris IPGP team, explains to me that the technology he uses was primarily designed to detect oil slicks at great depths:

> “The Critical Zone annoys oil companies, they prefer big contrasts, passing through limestone, sandstone, etc.. Because the CriticalZ, between 50-100 meters above, is altered with speeds that change a lot in the space of 20 meters down. Whereas, once you are at depth, it doesn’t change that much. The whole surface area, they just need to know if it varies, but it annoys them more than anything else. Because it’s more complicated, not homogeneous. What we study is the thing that doesn’t interest them. In oil seismic they are on larger scales and use larger energy sources like dynamite, or vibrating trucks, it has to be on flat ground and often they deforest beforehand to get through. We (CZ) do not share the same approach at all! Our data is more complicated, as are our terrain conditions.”[54]

Thus, the heterogeneous ‘near depth’ of the CZ is not known and de-

53 Jenny Druhan, 2019.06.01
54 Sylvain Pasquet, 2019.09.12

valued because it is of no financial interest, unlike the search for oil. The strength of geoseismic technique, however, is to image the soil without extracting anything from the field. It is even the opposite: it involves bringing a portable instrument directly into the field.

> <u>Fieldnotes from the Guadeloupe Critical Zone Observatory (Obsera), Quiock river, Basse-Terre, Guadeloupe, French Antilles, May 2019.</u>
> *A team of 6 people, including scientists, trainees and myself, is in charge of helping Sylvain with the geophysical measurements. The scientists tell me that we need to carry a portative instrument into the forest. My concern begins when we load the trunk with many suitcases and cables, increases when we reach the uninhabited zone and confirms when we engage ourselves into the slippery and muddy path. To my great despair, I realise that from there, even the path disappears. Imagine our group: cables around our necks, suitcases in hands or arms (as we can!), it's heavy because there are electricity generators, a hammer (I wonder: why?!), and another bag with a computer, receivers, cameras, tripods, lots of bottles of water (dehydration can come faster than we think) AND we have to climb up the side of the volcano directly in the stream, the only place that is almost clear of this dense forest! We transport the same equipment as the seismic oil industry, but here there is no road in the dense rainforest, so we transport these instruments on foot and not with the help of huge trucks that destroy the forest. The stream is not completely filled but there is enough water to be submerged up to the hips. It's a real test! Jérôme reminds us that we should be happy (maybe so that we can no longer complain): "imagine at Humboldt's epoch, when there was no medicine or repellent for mosquitoes, they must have been covered by bites". Oh yes, we should be happy... and we are! Scientists laugh, help each other, combine forces. Once we arrive at the place to be studied, we set up a sort of camp. Two of us draw a straight line by unrolling cables perpendicular to the current on either side of the river. The line is about 100 metres long. Nobody told me in advance how geophysics works, so I follow Sylvain's instructions carefully as I also help place the geophones in the ground, every 2 metres regularly and wire them. In addition, we have to place them in such a way that we don't lose them in the mud and decaying roots.* **(Fig.16)**

Geophysics conducts transects on either side of a watershed. They reveal

Fig.16. The installation of the geophones

(on the left) The difficulty of installing the geophones in the jungle. Lou Derry in the Guadeloupe CZO. Video still by the author.

Fig.17. Geophysics in action: hitting the ground!

(on the right) Once the geophones are properly installed and connected with electric wires, the scientists hit the ground with a hammer which generates vibrations that the computer records. Lou Derry in the Guadeloupe CZO. Video still by the author.

a gradient in the porosity of the rocks and soils that highlights the thickness of each layer. After placing the geophones connected to a computer and a hammer, the team is ready to get the measurements. Sylvain is at the computer, Lou is in charge of hitting the ground with a hammer, and Jean and Jenny relay the info: when Lou has to hit the ground and if Sylvain get a correct signal **(Fig.17)**. Once the hammer strikes the ground, the geophones record the propagation of seismic waves. The signals from geophones trace paths underneath which appear on Sylvain's screen who is seated among the tropical leaves **(Fig.18&19)**. The ground hears and vibrates back as the wave propagates. Between the source and the geophone, the propagation ray forms a path that follows Descartes' physical law of propagation speed of a sound: the ray is deviated according to the speed of matter. This data is then processed to produce images of the depths of the Critical Zone. Back from the field in the evening, Sylvain superimposes the combinations: in Guadeloupe, the scientists made 25 shots with 72 geophones, so there are 25x72 rays to analyse. At the IPGP where I interview Sylvain back from the field, he explains that there are different types of waves: propagation waves (the fastest and therefore the easiest to identify), shear waves (we don't see the fluids, we see the compression), surface waves (those caused by earthquakes which do the most damage) **(Fig.20)**. In order to map the near-depth of the CZ, Sylvain hijacks the geoseismic technique traditionally used in the search for oil. He selects part of the seismic signal and transforms the wave field from a distance-time to a speed-frequency. He doesn't look more precisely however, but he looks at another type of wave, generally unobserved because too complex to process. This technique allows him to apprehend the heterogeneous matter which changes considerably in just a few metres. With inventiveness, Sylvain reroutes a technique used by oil industry to apply it to the CZ. The change in the thickness and composition of the soil requires more care, it is not a question of seeing the very deep which is homogeneous but the intermediate layer of the soil which is much more complex. The images produced by the geoscientists are similar to medical X-ray imaging **(Fig.21)**.

Soil porosity in the Critical Zone

GEOPHYSICS
Soil composition
Images
Solid/fluid

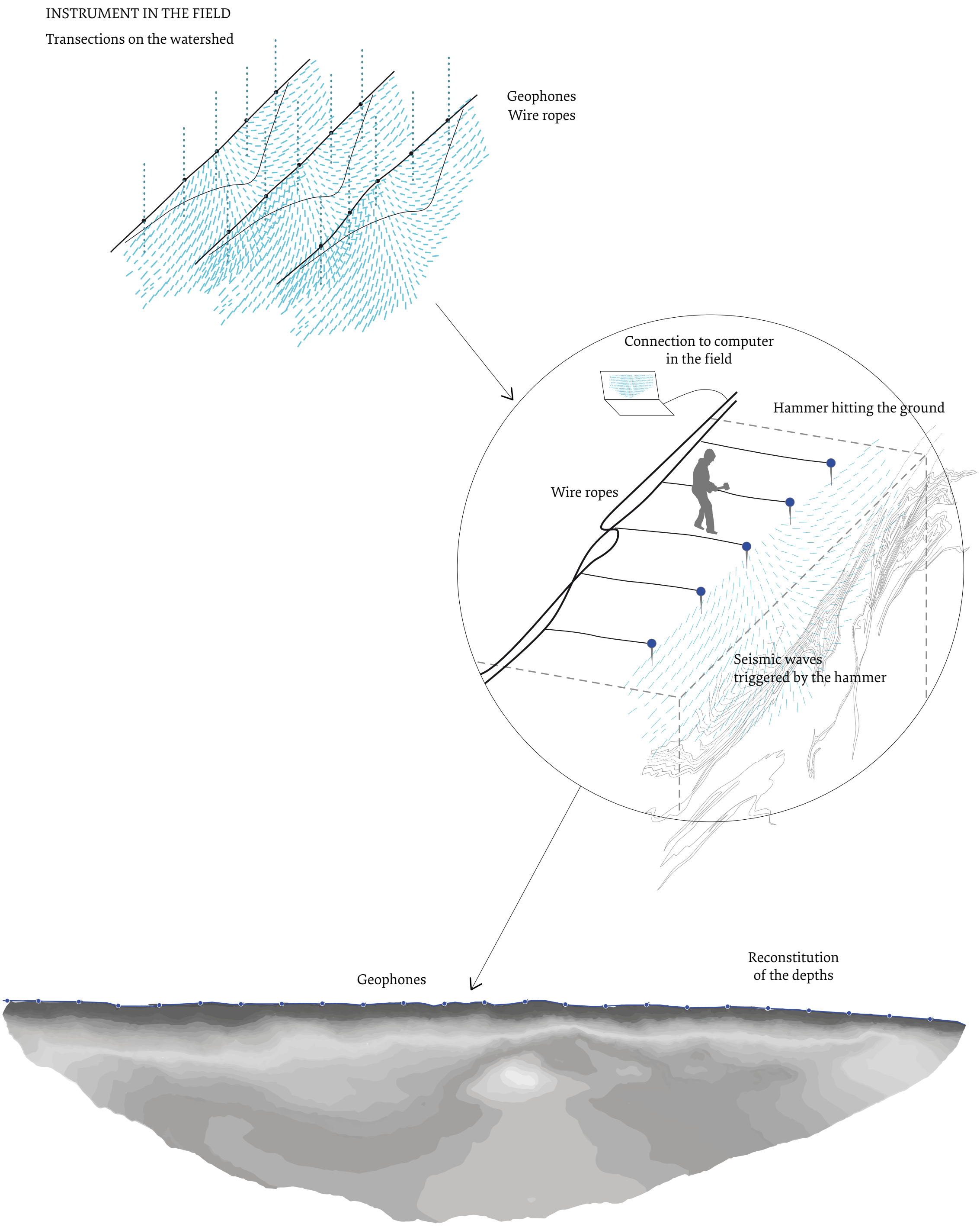

Fig.18. The process of the geoseismic technique

Diagrams explaining the process of geophysics with geophones. Drawing by the author.

Fig.19. The team of geophysics in action

The team gathered around Sylvain Pasquet, the geophysicien equipped with the computer, to help him collect data on the underground of the Guadeloupe CZO. Photography by the author.

Fig.20. The propagation wave

Sylvain Pasquet explains the propagation waves in the ground and how this allows the materiality of the ground to be reconstituted. Video still by the author.

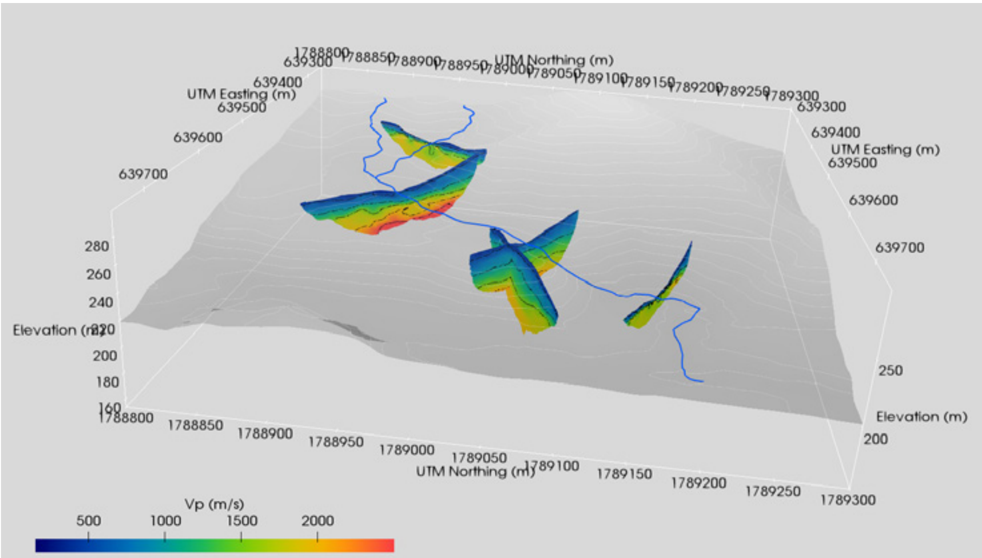

Fig.21. Quiock seismic profiles reconstitution

Results of the geophysics campaign at the Guadeloupe CZO, seismic profiles of the Quiock (the watershed stream). Image by Sylvain Pasquet.

Observing the ground means reducing myopia and blindness, but it is more difficult to reach the 'intermediate level' that is the soil than to observe the surface or the great depths. A series of responsive instruments is needed to inspect its composition, to explore the interconnections that are overlooked or invisible to conventional science. Some instruments are brought directly to the field, while other procedures require to slow down and maintain the tension between laboratory experiments and field sampling. These sensors capture the interior of the earth's body, what are then its components? What are the properties of the soil that we couldn't previously grasp? What type of soil emerges from the instruments?

4.3 Decomposing: erosion and weathering

Soil properties resulting from scientific observations relate to dynamic processes and not a stable surface. In this part, I will describe how the scientists see the soil as a milieu to be decomposed or which is itself in the process of decomposition. We will explore the various ways of decomposing the soil. The litter decomposition has to be differentiated from the rock decomposition, and the artificial decomposition in the lab.

> Fieldnotes from the Guadeloupe Critical Zone Observatory (Obsera), Quiock river, Basse-Terre, Guadeloupe, French Antilles, May 2019.
> *I have never been in such a flourishing landscape, around me a dense tropical forest, full of plants, biodiversity, humidity. I look around me, immersed! And then suddenly, my foot slips into a hole in the ground. I step on a root which broke instantly: I am not watching my steps, I am not paying enough attention to the 'field' –" be careful! Don't walk too close to the tree roots because the soil decomposes faster here", the scientist-explorers point out.*

A trip in the field reveals the classical misunderstanding of soil as stable and compact layers of matter. At the Guadeloupe CZO, Jérôme shows the team what remains of a leaf recently fallen to the ground: a lace structure **(Fig.22)**. The scientists investigate here weathering and erosion, the two processes that decompose the earth, as I learn from my own muddy and wet foot for the rest of the day. Within the CZ, soil is

Fig.22. Leave decomposition

Jérôme Gaillardet explaining to his students how biomass decomposes faster here than in temperate regions, showing a decomposing leaf, a lace-like structure, at the Guadeloupe CZO. Video still by the author.

rather unstable, with unexpected holes and above all: it decomposes. Julien Bouchez, geochemist at IPG, studies sediments and soil surface erosion. During his interview, he mentions that in Taiwan, one of the most erosive regions in the world, the erosion rates are 10mm/year, i.e., the surface loses 10mm per year. On the scale of a human lifetime, this represents 80cm. This geological time also conditions how fast the soil will reform. In Europe, the rate of erosion, i.e., the speed at which the soil is destroyed, is about 10mm every 1000 years. It is also the speed scale order at which soil forms at depth. Grain particles constitute the soil. In a dynamic movement, they are leaving and coming again. Those phenomena are called erosion and weathering. Weathering is a chemical reaction that transforms the rocks underneath into the soft layer beneath, generating the CZ. Without this reaction between CO_2 and the rocks, there would be no Critical Zone. In this sun weathering zone, the soil degrades, or erodes, while from below, new nutrients are released from the rocks: new soil is created (Fig.23).

Fig.23. Soil decomposing
Jérôme Gaillardet explaining to his students how soil decomposes faster here than in temperate regions, showing a decomposing rock, at the Guadeloupe CZO. Video still by the author.

This dynamic is fragile and occurs on a long period of time. Jacques Hinderer, geophysicist in Strasbourg working on the Strengbach CZO, dedicates long research to sinkholes. In his office, no lab but computers connected to instruments in the field, such as gravimeter, that we will describe later. The phenomenon of sinkholes occurs when the ground is collapsing. This happens after hard periods of drought in specific regions of the Earth. Underneath the soil, the water has disappeared, and the environment is porous and elastic: the pores close and the soil compacts. Jacques is able to detect and explain these variations of the ground level:

> "Most of the time, when the water table has subsided, the gravity (the force that attracts a body towards the centre of the earth, or towards any other physical body having mass) decreases: less water underneath, therefore less gravity. But there are places where the nature of the soil will cause the opposite. There is less water, but the compaction is very strong, so the soil sinks, and when the soil sinks, gravity increases, and it is this (reverse) effect that dominates. When the soil has not yet collapsed, the gravity decreases (because the water decreases or disappears) and when the soil finally collapses, the gravity increases (the water has not returned). In both cases it is caused by the disappearance of water with different processes."[55]

Counter-intuitively, the soil is stable because it holds water and collapses when water leaves it. Water confers to the soils the capacity to hold on, to support us! This soil disappears because the water is gone. Scientists are constantly observing the earth, a soil in ruins. I am surprised to learn that the soil holds together thanks to water, the soil is not solid, it is composed of grains surrounded by water.

The OHGE Strasbourg laboratory studies the CZO Strengbach, 80 km from the city. The special feature of the Strengbach is its long-term monitoring over a period of 30 years, making it one of the oldest CZO in the world and therefore also very well equipped with complementary instruments for geo-

55 Jacques Hinderer, 2020.01.17

chemistry, hydrology, biochemistry and geophysics. Marie-Claire Pierret is in charge of this CZO and works most of the time at her office at OHGE. I follow Marie-Claire throughout this building and its most astonishing part, into the basement. She opens a space of about 80 m2, filled with an impressive collection of materials. Bags of branches, leaves, rocks, soil, carefully classified by date and type, in storage drawers, a fridge filled with small bottles of water with numbers, dates and place of collection **(Fig.24)**. These are actually the archives of the Strengbach CZO. Each sample is processed into data stored in databases which are then accessible to the entire CZO network.

Fig.24. Storage of natural samples
Drawers filled with inorganic and organic material from the Strengbach CZO, stored in the basement of the OHGE laboratory in Strasbourg. Photography by the author.

Fig.25. Drawers of core samples

Horizontal drawers storing a 120 metre deep core from the Strengbach CZO, housed in the basement of the OHGE laboratory in Strasbourg. The granite core was sliced every metre and each drawer therefore holds one of these metres of rock of varying consistency. Video still by the author.

<u>Fieldnotes from the OHGE laboratory in Strasbourg, France, March 2020.</u>

Here the Strengbach CZO is decomposed into all the materials, pieces, elements, that the scientists need for analysis. And then, a treasure: drawers of core samples arranged horizontally by depth **(Fig.25)***. A depth exploration, but horizontally! Shiny materials, powdery materials, fractures, cracks, pale pink colours, transparent minerals. Every metre is a surprise. The core is well rounded, pleasant to touch. MC knows the history of every meter; her laboratory has mapped this 120-meter-long rock sample. She shows me her favourite area: "look here, at 80 metres, the water has altered the rocks into sand, we were surprised to discover it because we are on a solid granite mountain, so the water shouldn't be at such a depth". It may be because of the ice in winter, which increases the fracturing of the rocks (the temperature differential when the sun on the ice melts it more quickly and thus opens small breaches), or because of the roots of the trees. Scientists in the lab are still trying to figure it out!*

The sampling technique of rock at depth is called core samples which provides evidence about the composition of rocks. However, it is rarely done as it involves digging deep holes and extracting the mineral with an expensive machine (Fig.26). Core samples are however important because they allow the scientists to compare these materials with the scientists' hypothesises about heterogeneity or homogeneity rock composition. At depth, the rocks are never compact, solid. Fractures, i.e., faults in multiple directions (vertically, diagonally), incise, cut the mineral world (Fig.27). Along these faults, water infiltrates and flows rapidly in the direction of the fault, as well as potential organisms. The size of the faults could be different from one side of the mountain to the other. Thus, heterogeneity is determined when the faults are not in the same direction, causing the water to change its trajectory randomly. Therefore, fractures can thus sometimes be understood as producing great heterogeneity, and sometimes generating a milieu in its own. In some cavities, at the Larzac CZO in the south of France, the intrusion of CO_2 and water into the rocks at depth increases the rates of alteration and degradation, also known as phantomisation. The rock that has been eroded is called phantom rock, the dissolution of anything that can be dissolved. After a week in the field at the Strengbach CZO, I meet the scientists in their labs and offices at the OHGE lab, in Strasbourg, in March 2020. I follow Anne-Désirée Schmitt, a biochemist working mainly in the lab, in the white-room, that is a room sterilized where she studies the chemistry of samples from the site (Fig.28). Anne-Désirée works on the chemical interactions between soils and trees to understand the transfer of nutrients such as calcium. She manipulates tubes, syringes, small recipients to produce 'solutions' from a branch of beech that she collected on the site last year, keeping only the chemical concentration from the matter. Once the liquid is made, she goes to another room where a big machine is installed in the middle, this is a mass spectrometer which fractions the chemical, that is, dissociates each of the components (Fig.29). This process of decorrelation or deconvolution separates potassium and calcium for example. At the OHGE but at the IPGP as well, the lab enables scientists to understand why soil particles dissolve or are eroded and weathered by CO_2, water and sun. Scientists sample solid substances: leaves, rocks, branches,

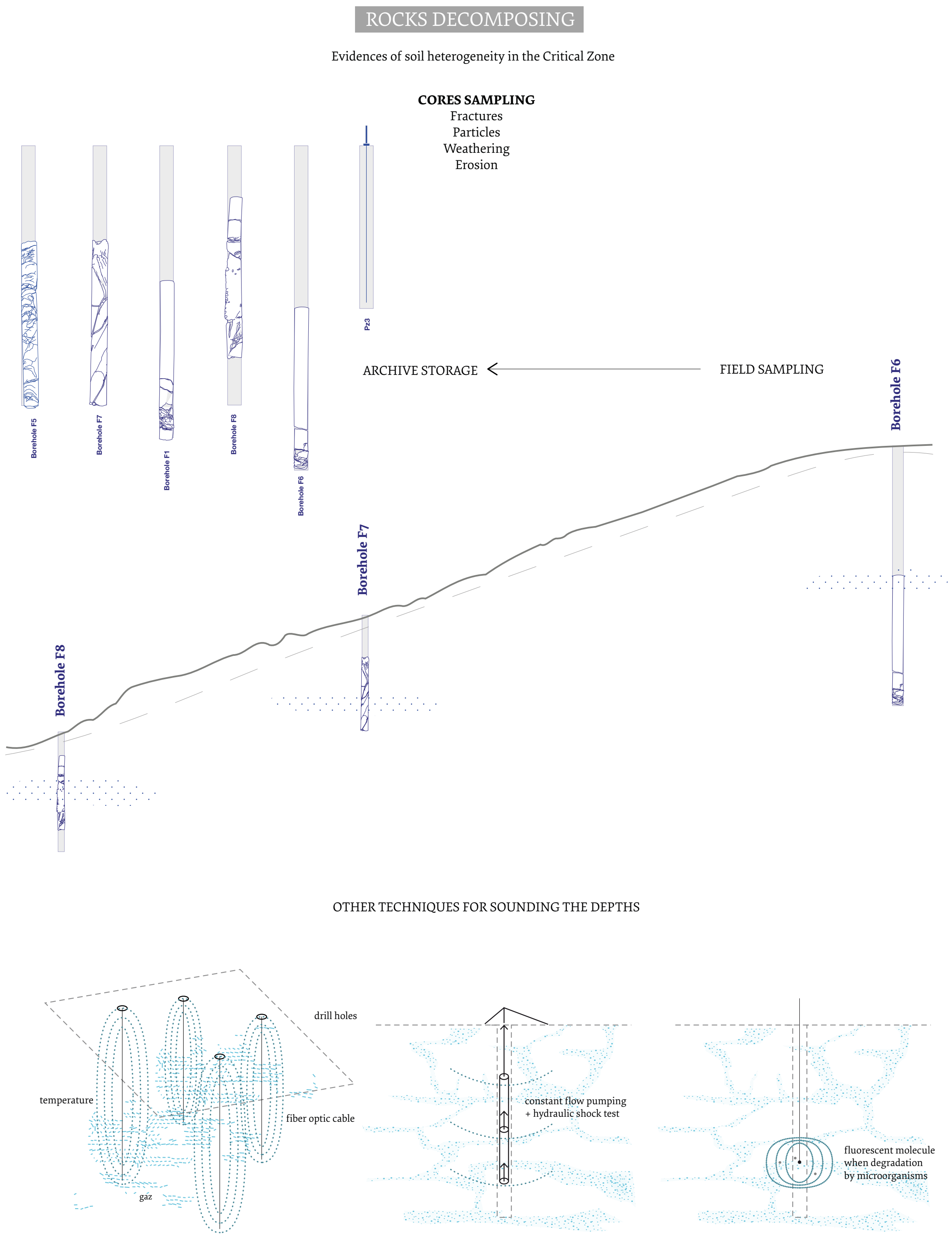

Fig.26. Ground investigation techniques

Diagrams explaining the process of core samplings with the example of the Strengbach CZO. Drawing by the author.

Fig.27. Granite rock core sample

Zoom on a section of the 120 meter deep core sample from the Strengbach CZO showing fractures of the rock. OHGE storage, Strasbourg. Photography by the author.

soil, and deconvolve (the scientific term meaning to decompose) them. In the lab, the scientists dissolve, decompose solid entities into small ingredients **(Fig.30&31)**. By doing it, they literally no longer see a soil as a block!

This part presented the successive emergence of disparate elements composing a soil. The instruments increase the number of entities that could play a role in the composition of the CZ. They populate the soil entity. The soil is decomposed by the scientists to grasp its properties: they extract pieces of rock, they deconvolve the earth, the dust. But soil is also decomposing matter in itself: when rocks fracture, when porous grains deposit, when particles erode and deteriorate, when compost decomposes, when mountains shift. These heterogeneous properties combine different scales, so that the soil is like a force field, a milieu, where phenomena of different scales intersect. As the soil seems to become so evanescent, what is the consequence on the constitution of the Critical Zone? Are the particles that the scientists trace sentinels of territorial controversies?

Fig.28. The white room in the lab

The white room is where the scientists decompose matter into «solutions» at the OHGE Strasbourg. Photography by the author.

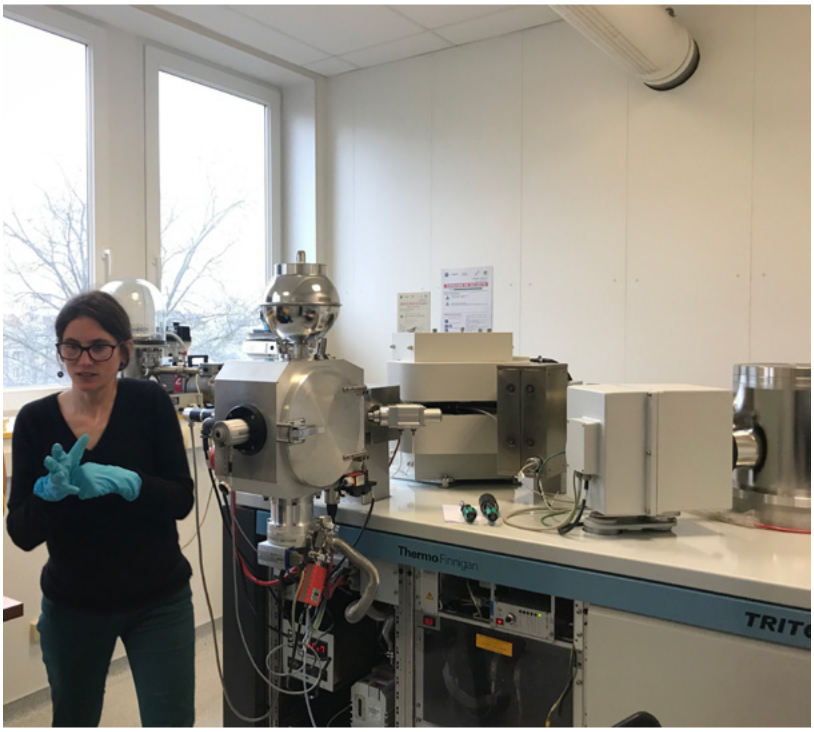

Fig.29. The spectometer

Anne-Désirée Schmitt explaining the operation of the mass spectrometer, the machine that decomposes each chemical element in a solution. Photography by the author.

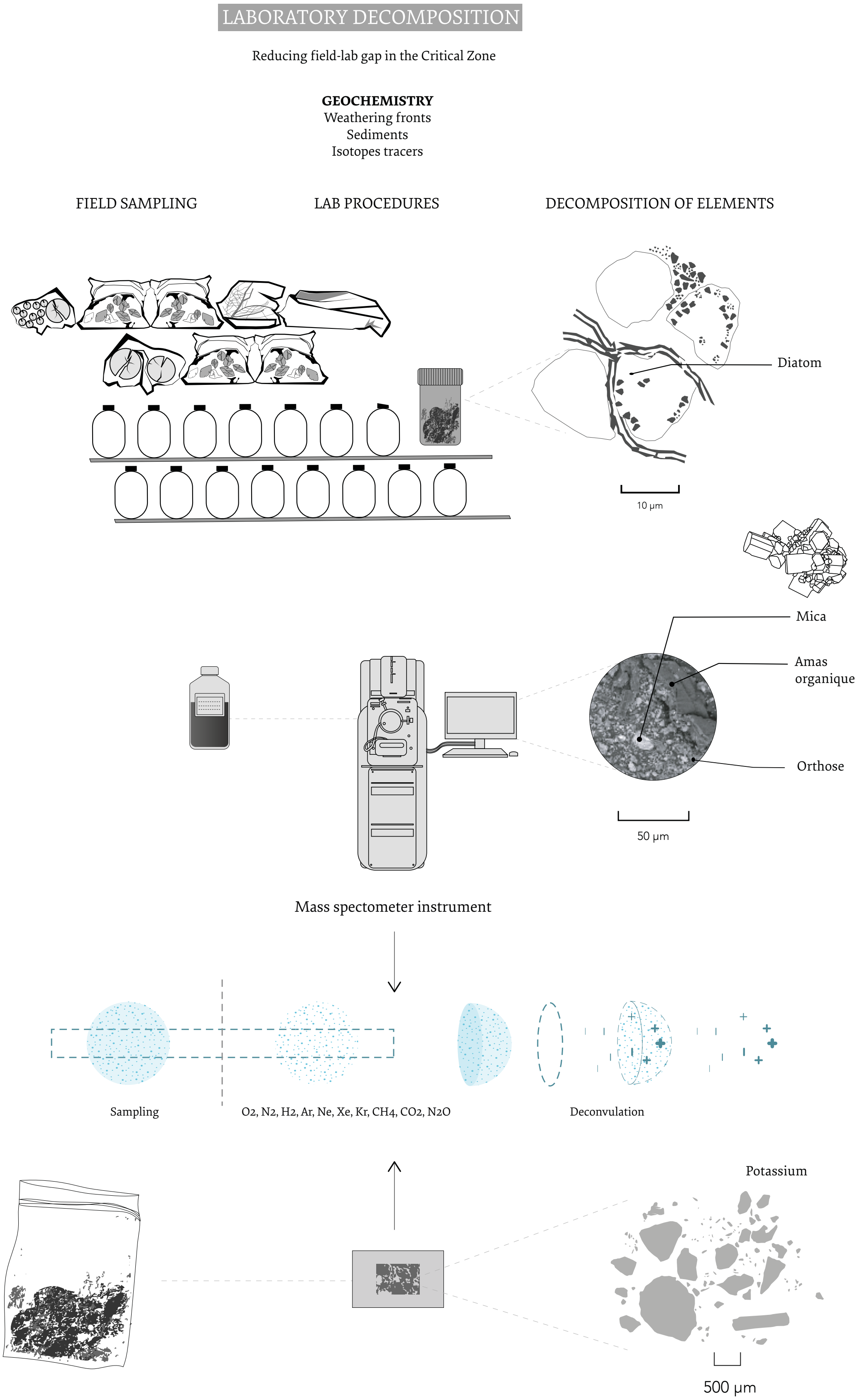

Fig.30. The process of geochemistry

Diagrams explaining the process of decomposition of materials in the laboratory. Drawing by the author.

Fig.31. The Soil and the Lab

Above, the soil of the Strengbach CZO. Below, the white room at the IPGP where the same soil is decomposed to be analysed. Photographies by the author.

4.4 Tracing: territory in struggle

The next part describes which knowledge the scientists gain from decomposing soil. Soil erodes and deteriorates faster than it is generated: holes, losses, debris and remains, reveal a ghostly soil. Geochemistry is interested in the remains, the tracers. Debris may also be what will remain of the landscape after intensive human land use.

After an intensive day of fieldwork at the Guadeloupe CZO with the geophones (see part "Observing"), I interview Jenny Druham, a geochemist from the US Eels River CZO (California), who is part of the team for this campaign. Explaining her research observatory, she expresses how the rocks, or rather the entire mountain, are moving:

> "It is geologically fast
> *the Earth is coming out of the sea* as a volcano,
> different kind of plate boundaries create *different environments*.
> It's actually *marine sediments* that you will find in the sea now, *that are coming out*.
> The rocks coming up are called *shales* out of the sea.
> It *weathers* into clay and this clay can be quite unstable and so it's possible to have *landslides*."[56]

Every time I think 'here is a stable, geological knowledge', unexpected movements are introduced by the scientists: even geology (which we think as a quite imperturbable period) is fast and unstable, the Earth is coming out of the sea, plate tectonics create wild frontiers, the nature of rocks leads to landslides. Moreover, it is not made of solid rocks but of tiny fragile creatures that are marine sediments! The soil appears as a territory in struggle. I interview Jérôme Gaillardet several times at the IPGP offices where I stay for a long period of time. As a geologist, Jérôme likes talking extensively on rocks. By sorting out the chemical elements, the active Earth has made rocks that are geochemical anomalies, like calcium sorted by multiple processes. The Earth decomposes and recomposes continuously. The CZ is thus the study of this 'weathe-

56 Jenny Druhan, 2019.06.01

ring front', that is the place and time where the rock transforms from the unaltered state to the altered state and gradually form soils (Fig.32&33).

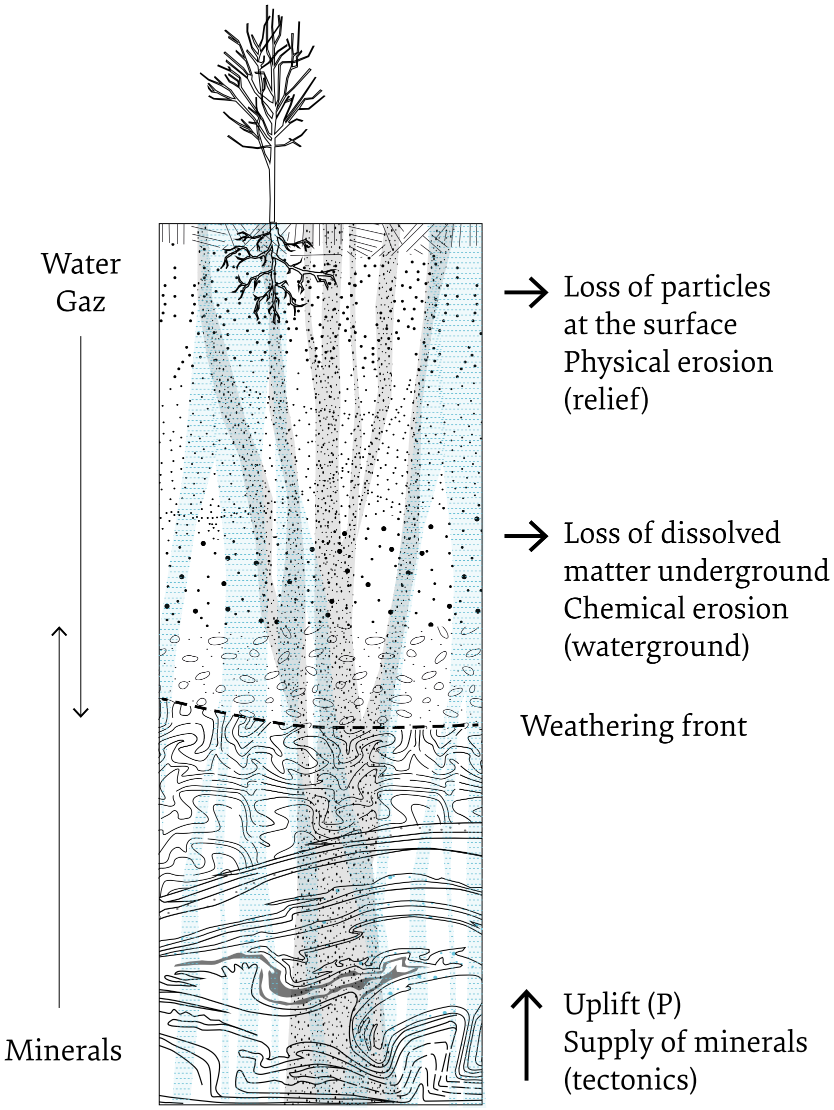

Fig.32. Diagram of the soil process in the CZ

Schematic cross-section of the Critical Zone showing how soil is formed by vertical processes and destroyed by horizontal processes. Drawing by the author.

This is a new vertical frontier in the ground, a dynamic frontier in time and not just in space. Each Earth layer is changing at its own speed. The decomposition and recomposition of soil structure leave traces that can be detected in particles. The vertical movement brings minerals up to the surface to recompose soil, but another lateral move exists. It is less known, and this is the sediment movement. At the IPGP, the team of the *geochemistry of the external envelopes* investigates large-scale terrestrial processes by examining 'debris', sediments sampled in the field, especially in rivers. For example, Julien Bouchez uses the variability of grain size in the river, which is related to chemical variability, to trace processes at the scale of the Amazon, which is one of the largest CZ observatories. It informs the scientists about the origin of the grains, from which region they come from, and the processes they underwent when they were transported through the CZ. He aims to understand how the grains are pulled from the surface of the mountains and how clays, i.e. the soils that cover the mountains, are formed. Julien is particularly interested in how sediments, the soil is also constituted from above, and not only from below when the rocks decompose. When a river is flooding, it brings sediments in suspension that will be deposited on the banks when the river returns to its bed and slowly making the meander migrate. This lateral move enables the scientist to know how much time sediments spend on the surface of the earth. A particle going deep into the rock stays 1000 years, but a sediment can be recycled superficially during 30 million years by processes, meaning that it spends more time on the earth's surface than in the earth's depths. Julien quantifies the weathering and erosion of sediments in order to determine how recycling occurs: how particles are deposited on the surface, how they are removed, continuously. During a discussion with Jérôme Gaillardet at the IPGP, I question him more about the definition of the Critical Zone, as he is the person who brings this concept from the US to France. After reflecting on his practice as a geochemist, he said: "The CZ is the reactive interface between the atmosphere and the rock, the damaged part of the Earth"[57]. The damaged part of the Earth... Indeed, the tracers that scientists use to understand CZ processes actually come from the debris, the residue of solid elements. I ask Jérôme what they

57 Discussion in Jérôme Gaillardet's office at the IPGP, July 2020

really look at when they analyse the processes: “the reality of geochemistry is slightly different from the reality of geology”[58]. Geology identifies the nature of each rock as stable blocks below the surface. Geochemistry identifies the source of the different elements. For this it uses ‘conservative tracers’: “we are not talking about matter but about a tracer, things that accompany matter, but by looking at the strontium isotope I can tell you where it comes from, the source. Like linguistics or botany, we don’t try to recognise the fixed but the movement, where it comes from, where it goes, how it changes.”[59] Geochemistry traces Earth movements but it can also be defined as the science of remains: “these tracers are the remains of something. Trace elements are memories of the history of the rock. There is a famous expression in our field which says: major elements, minor problems! The traces are spies, that’s what’s important.”[60] The CZ scientists are thus studying the traces, not the bulk of the mass, as in mineralogy, because when they see a boulder, they can’t actually understand the process and cycles of matter. On the contrary, the scientists look at the small to understand the mountain. Scientists understand how and in what period of time the soil degrades, decomposes, either through weathering (chemical reactions) or through erosion (lateral transport of material). If erosion increases, weathering decreases (no time for weathering because the material leaves, is exported too quickly). The CZ is a reactor controlled by the residence time (time during which the material remains in a zone) of fluids and solids. Here ‘critical’ is almost synonymous with disturbed, eroded, corroded, actively modified: water makes soil composition, holds the soil together. Porosity and loss of density characterise the transformation of rocks into soil, the weathered area. This also means great fragility. Indeed, the increasing speed of the weathering fronts is what worries scientists, and what they identify as the great acceleration of the Earth’s cycles triggered by human activities which is a manifestation of the CZ that needs to be dealt with. While deep geologists don’t have to worry about the urgency of the surface cycles that feed us, the CZ is precisely defined as the place of the acceleration of the cycles. In the summer of 2020, I followed the IPGP team in one of their observatories which is di-

58 Discussion in Jérôme Gaillardet’s office at the IPGP, July 2020
59 Idem
60 Idem

rectly impacted by cycles of disturbances. Focusing on the Orgeval CZO near Paris, we can grasp the full effects of phantom acreages and scalability process brought by the anthropocentric management of a territory.

Fig.33. A real version of the CZ section
A 1:1 cross-section of the Critical Zone in a quarry in Guadeloupe showing the rocks and the vegetation above. Photography by the author.

Fieldnotes from the Orgeval Critical Zone Observatory, Ile de France near Paris, July 2020.

The Orgeval catchment area/watershed has been an agricultural land, a pastoral landscape, for more than 2000 years. Today, however, the types of plantations rather evoke capitalist ruins: the same crop stretches out there infinitely, beautifully poisonous, golden blond colour - corn and wheat constantly sprayed with pesticides and fertilisers. This is exactly the type of plantationocene landscape described by Anna Tsing **(Fig.34)***. They can also be seen as ghostly acreages that feed Paris, the capital about 80 km away. Ghost acreages are the lands that are siphoned off by another land, slave lands in the service of big cities. But ghost acreages also because, in the field, we hear nothing. Summer has indeed been silenced. No birds, no other animals, not even the stream of water makes any noise when it flows. We are under a dome that would have drawn out all life, a ventouse that would have extracted the flow of life from this earth. Arriving in this desolate field, the three biogeochemists, Sophie Guillon, Jean-Marie Mouchel and Jérôme Gaillardet, carry out 'discrete' measurements, i.e. few samplings relatively spaced out in time. The team is studying rare trace elements such as sulphate, and the strontium, which is a source calcium tracer. The scientists don't look at the crop field, as if they were cynically used to it, they go directly to the streams where they have installed piezometers. All they have to do is collect the water from these piezometers on each bank and in the stream. It seems easy for once. But it doesn't go as planned, as always! First of all, reaching the streams is not so easy. We have to cross the corn and wheat. Who would have thought that the blond plants seen from the road are not at all sweet and that they sting terribly when we cross their domain! My ankles are already red. Soon my neck is too. Not because of the maize but because of the sun: it's about 30 degrees today and as we are in a plantationocene landscape, there are certainly no trees around to provide us with some shade and coolness (I wish I were in an agroforestry field...). I understand why no living creatures wish to settle there. It is in fact a ruin which we do not yet fully consider as such, and so we do not fully take the consequences that this implies. But can a real ruin be productive at the same time? Because indeed, these areas are productive, they produce gains and values. For the benefit of a collective farm? No, to the benefit of the markets. Without active human support - fertilisers, pesticides - the land would no longer be 'productive', even if productivity does mean wasting a* *lot of fertilisers and pesticides. Therefore, not only these fields are not productive, since they require large amounts of other inputs that could eventually exceed the yields, but also they destroy the soil and make it a ruin for at least a thousand years. Not only do they produce nothing, but they generate nothing either. In a complete and utter confusion, the region has been granted the status of NRP Regional Nature Park of Dairy Brie, even though no one makes cheese here anymore. A false good intention to become local again with a dead culture. Yet I feel guilty about writing this. We go through some small villages close to the CZO. Apart from the small town of Coulommiers, consisting mainly of a main street ending in a shopping centre, the surrounding rural landscape is half alive. We are told that the springs are no longer drinkable. There is a high concentration of nitrates in the water as it flows through the crops doped with fertilisers. But what we can't see, we tend to ignore. An old woman tells us it's safe: "I'm 90 years old and I've been drinking this water all my life!" I am too thirsty, so I take my chance.*

Fig.34. A ghost landscape
Wheat monoculture covering the CZO of Orgeval near Paris, a plantation landscape where diversity is erased. Photography by the author.

The scientists are now struggling among the stinging stems to find the piezometers **(Fig.35)**.

Fig.35. Collecting water samples in the ground
The scientists finally found the piezometers among the weeds on the banks of the stream. Photography by the author.

This area around the banks is very active ecologically. The piezometers are covered by a thick layer of sediment: soil, tidal swamp, deposits transported by the river. After few long minutes of digging under the scorching sun, they find the tubes that go down into the ground and extract the water that is trapped inside **(Fig.36)**. *They rinse the small bottles several times to sterilise them. When the right amount of water is collected, they filter it directly in the field. This takes time and work because the water is loaded with organic matter and the filter is therefore quickly clogged by this matter. The colour and physical composition of the water is not the same depending on the shoreline. The water table is about 1.75 m deep. This is not a lot because we are in the hyporheic zone of the river, i.e. an area that surrounds the riverbed in depth and laterally in the* *valley. The scientist draws a diagram to explain it to me. The hyporheic zone is a hot spot in the watershed because all the water from the surrounding depths comes here and thus produces a kind of "chemical reactor", where there are more transforming elements, more processes in progress, than elsewhere. I ask: "Do you consider that the water in the piezometer is also the water in the river?" Sophie doesn't understand the meaning of my question: "this is the hyporheic zone" she keeps telling me; Jérôme answers with a riddle: "Well, what is the river after all?", he continues: "we define an object for science but we realise that we constantly have to deconstruct it".*

Fig.36. The piezometer
Sophie Guillon takes water and soil samples in the hyporheic zone. Photography by the author.

The scientists proceed to the same sampling for the 4 other spots. It takes us all day. At the end of the circuit, we stop at a belvedere. The place of the old and impressive chapel offers a panoramic view of the landscape: field crops, linear roads, small stream with trees, church towers. This is the point of view that a western anthropol-

ogist exploring an exotic country could have experienced and he would have compared his perception of the landscape with that of the native who would probably have seen nothing interesting **(Fig.37)***. What does the scientist see now? I let him talk. To my disappointment, he seems to see the same as any occidental eye. But soon he speaks of another world: "There is a lot of evapotranspiration here because of these crops. There is also a lot of* CO_2 *here, the spring water degasses* CO_2*, we think it's the fertilisers that flow into the water table of the Brie, which is calcareous and therefore transforms the limestone into* CO_2 *because of a chemical reaction. Here we see how human activity influences soil formation by influencing the geological rocks". I can't help but think that we are no longer facing a landscape mapped by geographical means: I begin to see water particles floating above the crops, its opposite side being the cracked and dry soil; then I imagine that I scratch the surface to make an X-ray of the landscape and see how solid rocks become gaseous elements that are added to the atmosphere by water sources. I begin to see everything that leaves this landscape: water lost, soil lost, minerals lost, evaporated, dispersed by the flow of wind or water. A ghostly land, indeed.*

Fig.37. A new land from the CZ view?

From the belvedere, a panoramic view of the landscape surrounding and including the Orgeval CZO, a ghost landscape. Photography by the author.

It seems to me that the decomposing practices of the scientists are here mirroring in what happens on a territory. By a strange correlation, CZ studies indeed 'damaged part of the Earth'. The CZ could help understand, trace, the Anthropocene, as it puts in question our categories of studying, ways of seeing, a landscape. CZ searches for unscalable side-effects caused by scalability processes (mono-crops extended at large scale). It also gives some clues on how a ruined landscape behaves, a knowledge that could benefit for architects.

We have described how scientists follow the components of the soil in order to know their sources, trajectories (where they come from, where they go). To do this, the scientists trace the detached elements, the debris of the hard rocks. These debris enable them to know what happened to the ground and what the future dynamics of the ground will be. They observe an acceleration of erosion processes, i.e. the destruction of the soil without repair. This observation was embodied in a field narrative that took us into ghostly landscapes losing soil as a result of overexploitation. After its decomposition and tracing, how do scientists then manage to understand how soil is maintained, built up? What kind of connections hold the particles together?

4.5 Connecting: deep processes

Scientists replace a unitary view of soil with multiple threads they draw from their observations. In this part, we will describe how the scientists set limits to the CZ, define it as a space with different metrics, increasing our general understanding of the underground world. From the surface to the depths, the connections intertwine between the 'near-depth' world and the subterranean world.

The question what a soil is raises important questions for the CZ scientists on what the limit of the CZ is. For Earth System scientists (ESS), the thickness of the CZ on the scale of planet Earth is invisible. For CZ scientists, it is a problem of representation and of what is considered important. For farmers, the CZ scientists' definition of the boundary as what is wet at depth and up to the atmosphere is too complicated. For CZ scientists, we cannot escape this complexity. For geographers, the fact that scientists are not able to define the CZ boundary for any place on earth (such as measurements of geographic coordinates: latitude, longitude, altitude) reduces its credibility. For CZ scientists, this limit would be arbitrary. For CZ scientists, the limits of the CZ are what is observable from the inside with specific instruments. The CZ is also what absorbs solar energy, so the energy diffusion can set the limits. At the same time, however, this energy diffusion would be very unstable if it is measured using conventional spatial relationships. The state of the CZ varies according to time scales. Elements and particles enter and leave the compartments, are consumed by plants, transported by water, released by organisms, etc. The CZ is a zone of exchange, gas enters, is fixed, absorbed and transformed. The problem is that the edge of the CZ is never stable, but we are not used to depicting unstable things. How do you give shape to something that is continuously damaged? Likewise, the age of the CZ is not stable, an element rises to the surface vertically and then rises again laterally, it is a dynamic structure. How to define the contours of dynamic structures? Jérôme's early research on the formation of mountains and large rivers shows that the soil is the result and cause of the slowing down of a dynamic system. Indeed, when a mountain rises, erosion and weathering increase and the soil is rapidly formed and destroyed by landslides, until the thickness of this soil is sufficient to slow down the cycle. A self-protecting layer is created during this process over 200,000 years, which prevents water from accessing the rocks. Therefore, the soil protects the rocks so that weathering does not progress too quickly. If soil is removed, it speeds up the transformation of the nutritious rocks and therefore the surface layer generated by the weathering of these rocks will disappear because it will not have enough time to accumulate. The Earth is therefore both a source of nutrients for surface life and a producer of a protective surface to control the rate of erosion. Conversely, I am learning from the IPGP seminars that this thin protective layer can self-destruct. It is called 'rock cannibalism', when the same rock, the same sediment, is recycled several times on the Earth's surface and can be collected and analysed. Julien Bouchez studies the sediments which cover 60% of the Earth's surface. Sedimentary rocks are the result of the transport of sediments. Some other sedimentary rocks are just sand. The sand, over a long period of time, compacts and produces sandstone. It was once on the earth's surface in the form of granite, then it underwent weathering and erosion reactions, producing sand which became a rock again. What is transported by rivers is a material that has already passed through there. That is what they call sedimentary cannibalism, or cannibal erosion. Therefore, the soil does not have metric boundaries but self-generated boundaries.

Deeper than the sediments, scientists monitor the shallow depth by recalibrating deep earth instruments. As it would be the most important area on Earth, the connection between the deep rocks and the surface soil, the area where all the nutrients are exclusively created or recycled. But this zone is not homogeneous all over the planet. It is also difficult to qualify it, let alone set its boundaries.... However, this intermediate zone just above the water table can regulate major phenomena. Through Jenny Druham's interview and her lectures at the AGU event in San Francisco, I learn that her team at the Eels CZO (California) is trying to understand how the soil system retains water and supports the Californian forest ecosystem, which has been experiencing severe droughts and fires for several years. Scientists take water through the profile that transforms rocks into soil. In this profile, trees sink their roots into the soil. This space is difficult to observe and according to Jenny, "this hidden part of the CZ that has been so difficult to observe with normal instruments" could be "the most important part, the storage of the CZ."[61] However, this area has hardly any name, it is often confused with the soft soil (a few meters) and the rocks not yet weathered. The 'intermediate' zone is where weathering occurs, when rock is in the process of becoming soil. Many processes occur there due to the presence of organisms, water, nutrients and CO_2, in this zone without clear boundaries and often not represented on the soil profiles. Jenny calls this "rock moisture" because it is "above the aquifer" but "far below" the soil. In CZO California, they observe a strange composition: this zone is wet, but not completely wet, and these wet rocks could be the water that trees use to survive droughts, as their roots reach this depth. The depth to which the roots go down even surprise the scientists: they discover that it is about 15 to 20 metres below!

"If you think about it, there is rock deep down that is totally coherent,

61 Jenny Druhan, 2019.06.01

the rock that the earth is made of, and there are no pores, there is no room in that rock for water and since there is no room for water, there is no ability to weather, so effectively that rock has not entered the Critical Zone yet. So, you can think that is below the CZ all the way to the centre of the Earth. And on the other end of the top, there is soil that is totally engaged in sustaining vegetation, carbon cycling and all the rest where we grow our food. And there is a depth between those two and that depth is the subsurface of the CZ. It's the section of the earth that is open enough for water can get in. Why is it as deep as it is? Why isn't it two centimetres' depth from bedrock to soil? Why isn't it a hundred kilometres from bedrock to soil? We don't have an answer! There is a balance of many different processes that set that depth and that's what we're trying to understand. It varies from place to place with all the different conditions."[62]

Jenny suggests a wonderful definition of the soil as the part of the earth that is open enough for water to get in. Life is about leaving space, making pores, making interstices. Then, the so-called fixed limits are in fact a question of balance between something that goes in, and then erodes, and comes out, and then recycles. Scientists study the transformation, the in-between, the processes accountable for change. The intermediate zone, the near-depth, the subsoil, this damaged part - the regenerative part of the Earth, is the new exploration.

In the hall at the IPGP, a reproduction of Kircher's engraving is hanging. I am surprised to see it in a modern science institution **(Fig.38)**. This *interior of the Earth* is indeed an old version of the Earth scientifically inexact. However, it must reflect some truth, otherwise it would not be displayed here. In this image, turbulences, deep connections, resonate with Jérôme Gaillardet's explanation of what happens in the deep core of the Earth:

"In the core there are also rapid cycles: magnetic storms, linked to super-active convection in the core, which occur in a few hours, but they are events, not cycles, for a cycle it takes a billion years to re-

62 Jenny Druhan, 2019.06.01

turn to the same point."[63]

Fig.38. The lobby at the IPGP with a reproduction of Kircher's map

Athanasius Kircher, *Interior of the earth*, 1678. The map shows subterranean lakes, rivers and fire pools: a dynamic Earth and connections across the depths. Photography by Jérôme Gaillardet.

If there are movements at depth, how do the scientists follow them? The gravimeter shows evidence of Earth connectedness at depth. There are only 50 such expensive instruments in the world, called 'i-grav': notably there is one in the Strengbach CZO. Gravimetry stations are sheltered in a secure space at the top of a CZO. Jacques Hinderer is responsible for the measurements and analyses of this gravimeter. I meet him at his office in Strasbourg, at the "Institut de Physique du Globe de Strasbourg". The gravimeter measures fluctuations in gravity from the distribution of varying densities and masses within the Earth. The technology consists of a ball levitated in a gas, moving accordingly to the variations in gravity. As the gravimeter sends these mass fluctuations measurements in real time to the lab, Jacques shows me these

63 Jérôme Gaillardet, 2017.07.17

variations on his computer's screen **(Fig.39)**. The back and forth between the field and the lab is automated here. Real time means second after second. Depending on the time window that Jacques is choosing, either a day, a month or a year, various phenomena appear. I am used to following the scientists in the field physically. Here, Jacques connects his screen, and there, under my eyes, the Strengbach observatory situated in the eastern France Vosges forest appears. Time and space become intertwined in his office. He unravels the waves on his screen by increasing the time window of his software. As he explains, the recordings are an "assemblage of long time series in which we can see things". With this instrument, the scientist reconstitutes a world of hidden underground connections **(Fig.40)**. Indeed, the gravimeter is able to record the tidal waves breaking on the North Sea coast hundreds of kilometres from the Vosges forest! Jacques shows me on the screen:

> "Waves breaking on the coasts are responsible for these things (he shows me the graph): in blue, these peaks, in between two peaks there are 5 seconds, it is one of the fundamental periods of the microseismic noise that is generated by the waves. So it's a direct implication of these waves, it's the blue signal. The sources of the microseismic noise are in the ocean-land interaction on the continental shelves."[64]

These sounds are microseisms induced by the interactions of the oceans with the earth, the breaking tides that cause waves on the surface of the earth's crust and can be observed anywhere on earth. The Earth is suddenly transported into the office. The gravimeter is a very sensitive instrument, it is both its strength and its weakness, it is sensitive to everything, any redistribution of mass nearby will cause gravity to vary, depending on the water in the ground, or the air pressure, or the movement of the ground, or the influx of magma from volcanoes, or the melting of ice. All of this changes gravity. Large earthquakes far from the Vosges can be felt and generate 'co-seismicity'. These earthquakes, tremors, vibrations, are imperceptible to humans but some animals can hear them. Thanks to the gravimeter, it is possible

64 Jacques Hinderer, 2020.01.17

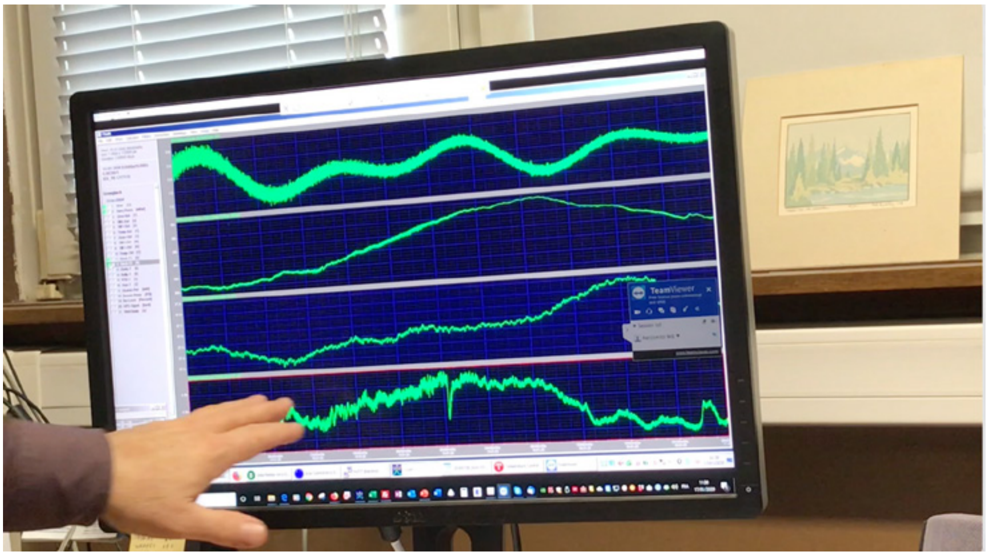

Fig.39. Jacques' screen showing gravimetry sequences
The screen of Jacques Hinderer in Strasbourg, directly is connected to the gravimeter of the Strengbach CZO. Photography by the author.

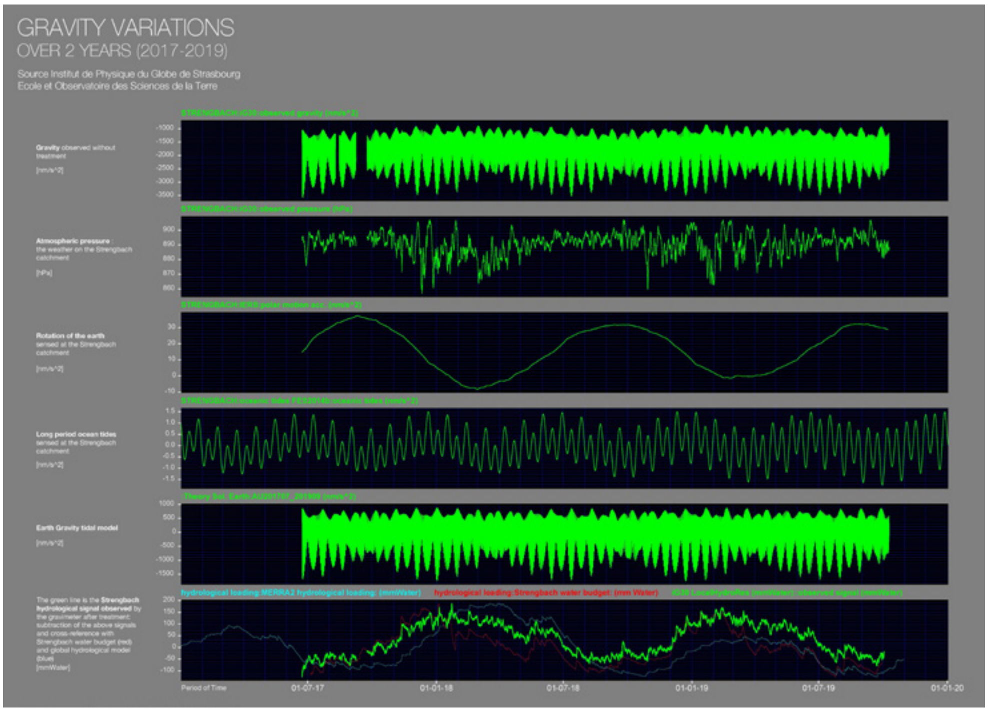

Fig.40. Graphs from the Gravimeter
Data from the gravimeter at the Strengbach CZO showing the various phenomena that cause gravity at the Earth's surface. To obtain the last line, the hydrological signal of the Strengbach watershed, the scientists have to subtract the other signals: atmospheric pressure, rotation of the Earth and ocean tides. Reconstruction of Jacques' screen, drawing by the author.

to identify the type of gravity that is observed: the gravity resulting from lunar tides, the gravity resulting from atmospheric pressure, the gravity of the earth's core, which causes a resonance effect (a wave that is more amplified than if the core did not exist) and finally the hydrological signal which is the signal that scientists aim to monitor in the Strengbach CZO to understand how the water resource at depth is recharged in the water table **(Fig.41&42)**. Echoes, resonances, diffusion, transport, the gravimeter records the stories of the earth, the earth tidings, its inaudible sounds and vibrations. By framing the time window on a day, scientists see the tidal cycle. Monitoring something happening at a distance questions common sense of spatial territorial boundaries. There are effects of embedding places on the earth, of recursivity (a phenomenon that returns every day) and of revolution (circularity of the horizon).

The soil is not a static entity but made up from a series of active transformations: construction of a protective layer on the surface, metamorphosis of the rocks at depth, recycling from the depth to the surface. These transformations cannot be assigned to particular scales or vertical boundaries. However, scientists delimit two areas of importance. The first is the "near-depth", which can be the storage of water and organic material in the Critical Zone that allows all forms of life to exist. The second is the "subterranean", where hidden underground connections can link phenomena in different places on Earth. We learn from the scientific practices that the soil is either a local place or a global condition. Subterranean depth ties various places, while near depth holds global cycles.

SUBTERRANEAN CONNECTIONS

Recording Earth tidings in the Critical Zone

GRAVIMETER
Tidal waves
Core
Pressure
Groundwater tables

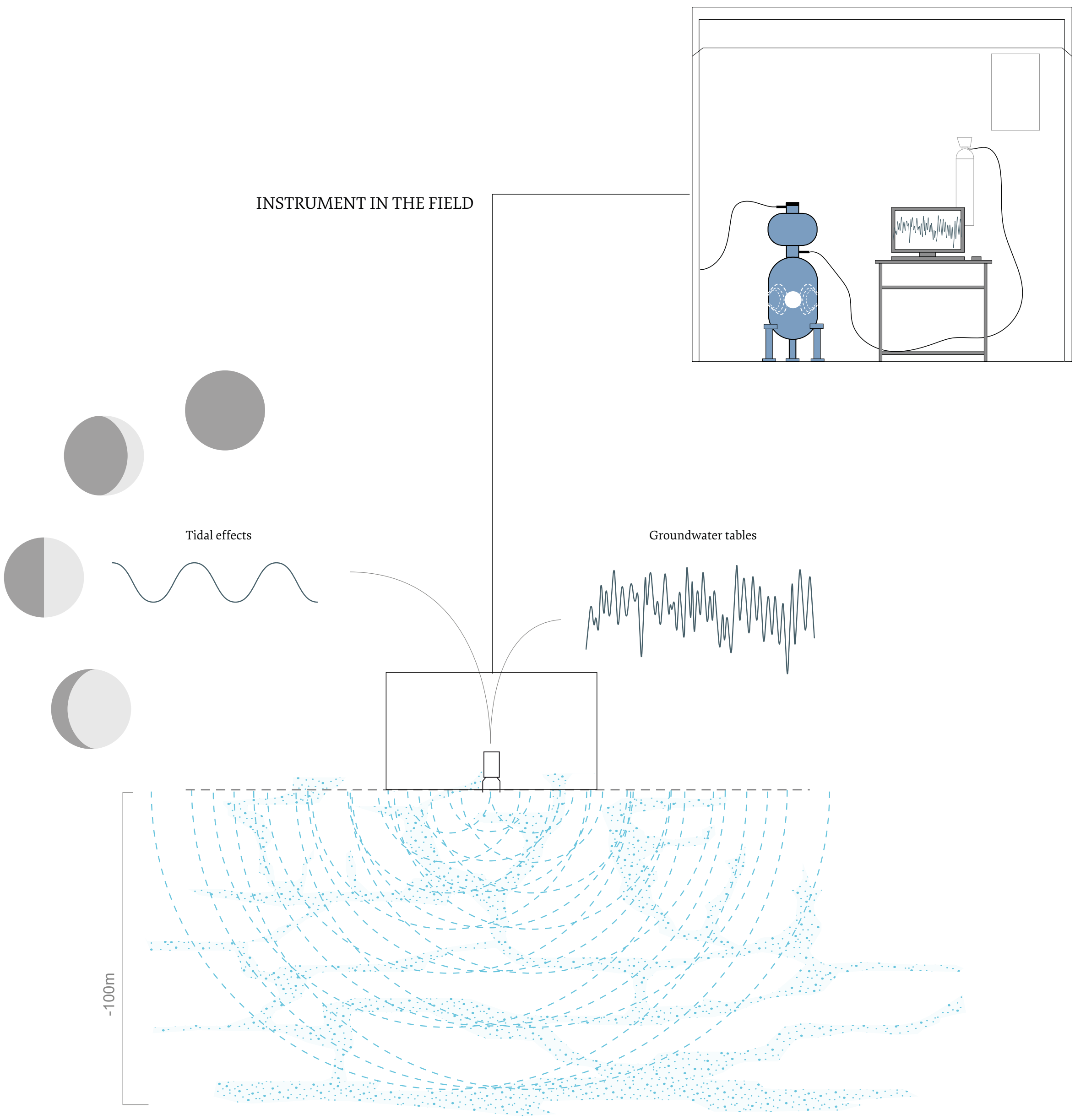

Fig.41. The Gravimeter technique

Diagrams explaining the operating process of the gravimetric instrument. Drawing by the author.

Fig.42. Gravimeter and karst

Above, the room where the gravimeter is housed at the Strengbach CZO. Below, a karst environment at the Larzac CZO where another gravimeter is installed to probe this particular underground. Photographies by the author.

4.6 Conclusion: a world of many earths

Some instruments are brought temporarily into the field, directly placed on the ground, such as seismic geophones, tube for sampling, machine to extract core samples. Those instruments are hijacked by the scientists, who recalibrate them so that they can probe the surface depths, as geophysics. Multiple instruments are needed to account for the ground, which remains opaque, an unknown with impenetrable matter. However, most of our graphic representations don't show the soil under the surface, focusing on the horizon or, when cut sections are used, the soil remains a dark matter. Soil is a cartographic unthought object. However, we see in this chapter that the instruments are important in allowing us to see differently. As a consequence, it may be useful to restore the drawings of the instruments we used to draw the maps, so that we could see the changes between a view from above (by satellites) and a view from inside (by CZ instruments), as past scientists did like Hooke and Humboldt. The trips back and forth between the field and the laboratory that the scientists do, or the importation of laboratory instruments into the field, aim to decompose the soil so that the processes involved in its formation and destruction can be analysed (through sampling or image reconstruction). A series of soil properties emerges from these analyses: heterogeneity, fractures in the solid matter, wetness, particles, vertical but also horizontal movements, and porosity, a quality rarely associated with soil that architects most often see as a stable block. Soil crumbles, moves, collapses. Soil is the surface layer of the planet that erodes, so it must be differentiated from the earth's crust, which is much more stable. As a consequence, focusing the study of the Anthropocene on rocks may be reducing, as the turmoil undergone by the soil cannot be reduced to the geology but expends on a much more complex understanding where cycles and long-time scales, horizons and erosion intermingled, which introduces new timescales and overlapping times. Scientists are studying the damaged part of the Earth; they are tracing the earth in motion through the remains of decomposing rocks into particles. In some places, such as the Paris basin, the soil on a large scale is disappearing, decomposing because of intensive use. In this chapter, we have shown how the scientists trace the disappearing entity to write its history, resulting in what historian Pomeranz calls “ghost acreages”. Scientists trace particles, mass loss, debris, and thus observe the acceleration processes responsible for soil loss. Tracing soil shows that soil is not a ground and that ground is an invention that promotes an idea of stability: soil is in itself an alteration process, with erosion and alteration fronts (disintegrate and reform). So the surface, the horizon, is never at the same level. As a consequence, there may be territorial ruins that we don’t acknowledge as such. The presence of the scientists is indispensable to reveal these biogeochemical ruins. However, we don’t have the right tools to visualise these degradations of the state of habitability of a territory. One of the solutions would be designing a tool to link science on cycles and land managers. However, this tool is not simple to conceive. The soil of the Critical Zone is difficult to grasp: it connects different phenomena and places, its spatial dimensions are not well-known with the near depth, mysterious and yet essential for environments, as it maintains the biosphere and is still largely under-instrumented. The boundaries between soil layers are not delineated and permeable, they overlap. Overcoming the pitfalls of metric scales, the subterranean connections at depth redistribute the boundaries between the local and the global, the closed and the open, by linking distant places such as coasts and mountains together. As a result, this defines a new ground, deeper at the local point, and at the same time more extensive at the scale of the Earth. Soil appears unscalable, without strict boundaries but depending on each land: common metrics are unsuitable. As a consequence, taking a cosmopolitical view on soil may mean introducing new relationships with the Earth, not as a global entity with global metrics and localisations (latitude, longitude), but instead adjusting each representation to the soil which is mapped. We would end up with a diversity of *Earths*.

5 Rivers

5.1 Introduction

The usual understanding of rivers is that it is a flow cutting the land and bringing water for life. The river is restrained to its beds, minor and major. Understanding rivers has several crucial purposes: predicting floods, measuring resources for both humans and non-humans, and assessing water quality in relation to pollutants. In this chapter, we will follow what a river is and how the scientists trace the complexity of this natural entity, which is usually traced as a line on geographical maps. We will see what the river is when we follow the work of the scientists. Following the practices of the scientists, this chapter is divided in four categories which are the same than those used for the previous chapter on soils, as illustrated by the diagram below. The first part 'Observing' follows the scientists in the field and shows how rivers require a specific instrument to observe them, which bridges the gap between the field and the laboratory and reconfigures both science and the territory under monitoring. The second part 'Decomposing' explores how, thanks to this new observation approach set up by the scientists, the river decomposes into many elements, all of which having their own behaviour. This broadens our view of what a river is, and instead of a geographical unity, scientists introduce a multiplicity of rivers, each with different properties. The result is what could be called a plurality of rivers, a pluriverse following William James' term. In the part on 'Tracing', we will see how the scientists make sense of this plurality of rivers by following water and its chemical elements through the different parts of the CZ, unpacking surprising notions such as the ages of water. The last part, 'Connecting', follows the CZ scientists as they offer a new vision of rivers as sensors, sentinels of the global earth cycles and their disturbances.

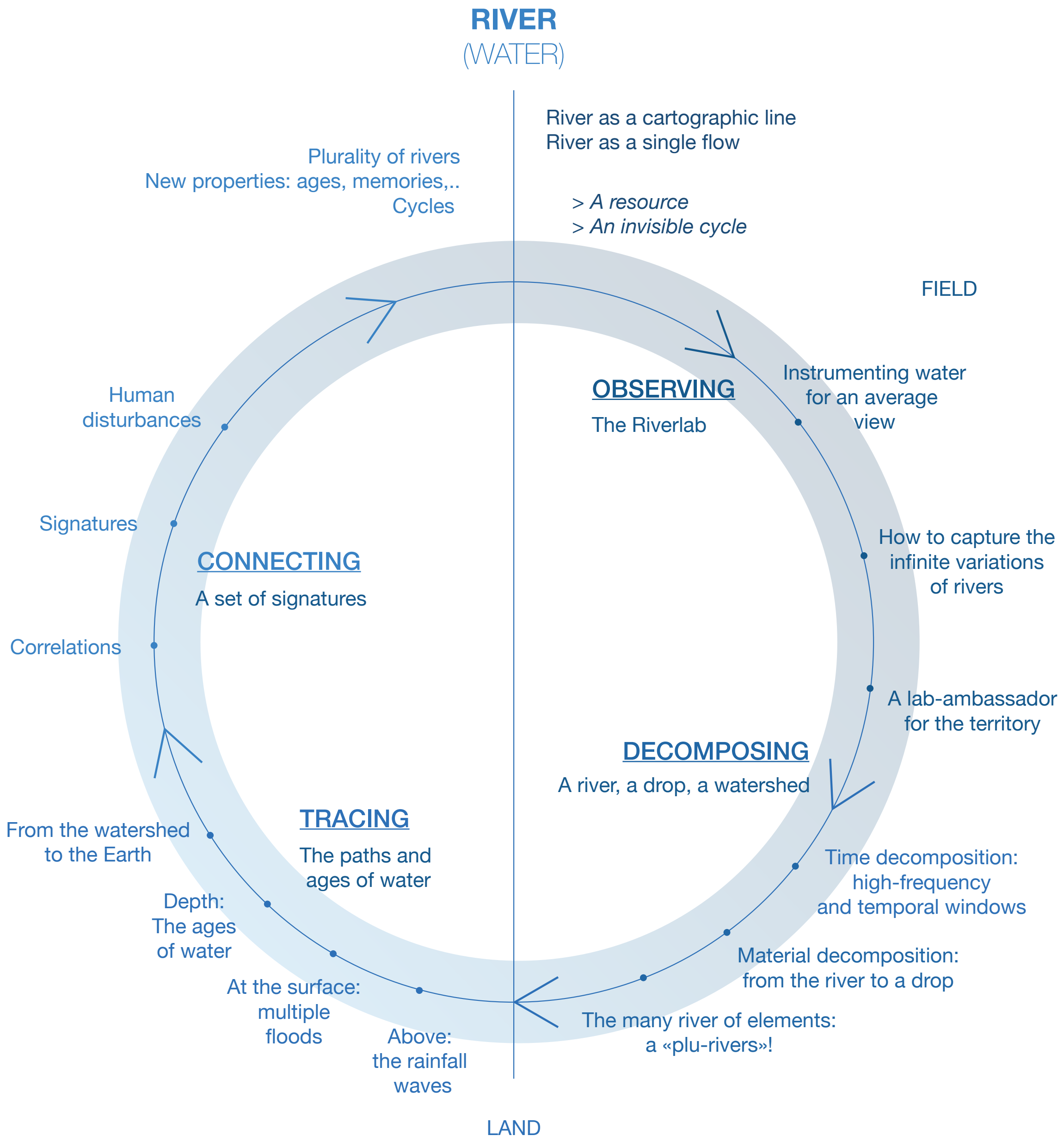

Diagram 4: Chapter RIVERS

5.2 Observing: the Riverlab

To monitor the variations of rivers, the scientists need to develop new instruments, to adapt procedures and relationships between the laboratory and the field. The Riverlab is a specific spatial instrument which allows the difficult observation of rivers as they change throughout the days, the seasons or events.

CZ scientists are developing strategies to observe the invisible materiality of soil and rocks at depth (see last chapter on soils). Other strategies are needed to observe water. How to capture and observe its flow? In setting up methodologies (procedures and instruments) to observe and measure water, scientists are dealing with three difficulties. Firstly, since water is everywhere, in the river, from top to bottom, but also in the ground, sometimes at great depths, where can it be observed? Secondly, since it flows, it is a mobile fluid, how can it be captured? And thirdly, since it changes at every moment, how often can it be measured? The watershed is the geographical unit of an observatory. Hydrology, which studies the paths of water on the surface, introduces this notion. In a CZO, water is measured at different points in the watershed, but more extensively at three main stations: the meteorological station (where the water 'falls'), the springs (where the water 'gushes' from the depths) and the outlet (where the water 'exits'). These three points make it possible to reconstitute the watershed. The lowest point, at the outlet, is particularly important for geochemists. In his research, Julien Bouchez, geochemist working at the IPGP in Jerome's team, studies how rivers export the products of the reactions that occur in the CZ. The chemical composition of these products gives an idea of the processes activated at the watershed scale. Thus, the river's outlet provides a kind of average view which bypasses the extreme heterogeneity of the CZ. A local sampling of the water, a single point in the correct location, could provide an understanding of the entire watershed. This underlines the crucial role of water in the CZ as a flow that carries materials and chemicals. Water is an important element of the CZ. Most of the scientists I met, especially at the IPGP, study water at some point. Some of the scientists are potamologists, that is specialists of rivers. This is the case of Jérôme Gaillardet who has taught young scientists to become sensitive to it. Among them, Paul Floury, whom I interviewed extensively, speaks on behalf of water:

> "At the end of the winter and the beginning of spring, the water is fresh, reactive, corrosive, there is a lot of brewing. As there is a lot of water, the erosion is about 80% at this period. At the end of summer on the contrary, the water becomes brown, very concentrated, it doesn't dissolve well, and it is older. This is called the low water level phase; the water dries up. Thus, there are various regimes of water. Moreover, the river is dynamic and actives throughout the day. With the light radiation the river is suffocating, it feels the effects with a phase difference, as a delay of response. It is not an unequivocal system but pulsatile day/night, consequently erosion is impacted by this flash. In winter the flux is colder, darker, mechanical. Thus, we could feel it too, it is a kind of potamosensorial thing."[65]

The Critical Zone is filled with water, washed, clear, or brown, charged with sediments… Water is not only in the running river, but it flows everywhere. For the scientists, the water varies depending on the season and the events. Thus, it has to be sampled regularly to understand its variations **(Fig.43&44)**.

Fig.43. Sampling rivers
Sampling methods at the Guadeloupe CZO. Samples are collected directly in the river (left), in a water retention basin (middle) or at the gauging station (right). Photographies by the author.

65 Paul Floury, 2019.11.11

Fig.44. Sampling tools
Sampling methods in the CZOs Orgeval (left), Strengbach (middle) and Puerto Rico (right). The sampling practice is common to all CZOs. It involves carrying bags, tubes, bottles, filters, pipettes, etc. Photographies by the author.

But scientists in the Critical Zone inherit from the lab methods of research, including the sampling method, which consists of collecting water in the field and bringing it to the laboratory for analysis **(Fig.45&46)**. This method is not really adapted to account for the variations: the researcher cannot be physically in the field every hour or every day. Thus, observation is limited by the number of samples taken and the researcher's ability to analyse them. Here the laboratory reaches a 'glass ceiling', it reaches limits in the understanding of nature's variations. Scientists can therefore miss important events. Water quality is highly variable according to the seasons, floods (which can occur in less than an hour), day and night. The scientists may miss how the watershed will react to an increase in certain chemical elements such as nitrate, which can have a major impact on drinking water, as Paul explains:

> "In periods of low water, of drought, we see a beat which is the day-night variations, the impact of solar energy on the river which will react and have an oscillation between day and night, i.e. it will be very sensitive to evapotranspiration and concentrations will be impacted."[66]

66 Paul Floury, 2019.11.11

Fig.45. Water analyses in the lab

The samples collected in the field are then analysed in the laboratory, in this case the OHGE laboratory in Strasbourg, where scientists filter the water from the Strengbach CZO and analyse its chemical composition. Video still by the author.

Fig.46. Storage of water samples.

After being analysed, the water samples are labelled and stored in a refrigerated room, here in the basement of the OHGE laboratory building in Strasbourg. This sampling method requires large storage spaces. Video still by the author.

The variations are triggered by the sun, which generates a pulsating energy signal, a light wave that will cause evapotranspiration and modify reactions. These variations cause the river to behave differently. The difficulty is to capture the changing nature of the river and its unpredictable behaviour with traditional samples, as if the river was alive, a huge monster to capture: "The river suffocates under the sun's energy, it will retract at the end of the day more deeply, hiding. Every day it undulates deeper and deeper."[67] The sampling method offers only a fragmented, blurred vision, or even a "chemical myopia". Sampling analyses provide a 'trend', not the precise evolution of the water response, which is called a 'signal'. Paul defended a PhD at the IPGP, under Jérôme's supervision, which aimed at increasing the observation of this signal. As some of the scientists on his jury pointed out, sampling is "a bit like wanting to listen to Beethoven's symphony with only one note every five minutes: it's not audible. If you want the whole symphony, it's better to have a continuous analysis."[68] In order to solve this limitation, this lack of measurements, the group of scientists of which Paul was a member invented the prototype of a new machine, the Riverlab, during his PhD, supported by the French CZ network OZCAR and CRITEX[69], a program financed by the government to develop new instruments for monitoring the CZ. The Riverlab is a very specific type of mega instrument, a cabin-like architecture installed in the field, at the outlet of the watershed near the stream. Inside, there is a kind of mini laboratory. The Riverlab is a green container manufactured by an enterprise according to the scientists' plans, developed around how the lab could function semi-automatically inside it. However, it is not an entire lab but a small miniaturised one only for the sampling and analyses of the river, that is why it is placed near it **(Fig.47)**. The innovation brought by the Riverlab is to sample the river in real time, to follow its changing states when they happen and so without the delay of the sampling methods. The Riverlab is not really an instrument but a setting, like a big operator at human scale. This in-between instrument combines the need to sample, to be in the field and to bring these samples in the lab to analyse

67 Paul Floury, 2019.11.11
68 Report from Paul Floury during his interview
69 The CRITEX investment programme enabled Paul to prepare his thesis on one of the prototypes developed (with Jean Louis Roubaty, Gaëlle Tallec, Patrick Ansard)

Fig.47. The Riverlab, an outdoor lab
The Riverlab is a small architecture housing instruments similar to those found in laboratories to decompose water chemistry. Here, they are located directly in the field: the Riverlab is a new kind of outdoor laboratory that brings a new dimension to the territory. Video still Sonia Levy.

them. The Riverlab does these operations. As the scientists cannot displace the entire lab, the riverlab allows the lab to travel, to be entirely deterritorialised, and to perform more complex operations than the sampling. It is a way to bring the laboratory close to the river but also the river close to the laboratory, as a meeting halfway through. This hybrid dispositive between lab and instrument relates more with its territory than a simple instrument does. Indeed, it brings the territory closer to the lab. The lab is no longer understood as this static place, this institution where experiments and measurements are conducted, but it is distributed. It is deterritorialised so as to be closer to the phenomena it explores and it is also adjusted to the specificities of the phenomena, well-adjusted to the river so that it better measures the fluidity, the changing chemicals and the flows. A tube with a pump brings the water inside the machine and through circuit filters the water **(Fig.48)**, then, only a drop of filtered water ends up being analysed, revealing the composition of the river **(Fig.49)**. Four Riverlabs are now installed in four CZOs (three in France and one in USA) and Paul is developing it for more sites. The Riverlab is indeed mostly generic but has to be always calibrated and adjusted for each site, so that Paul often has to travel to install or repair them.

Fig.48. The stream analysed by the Riverlab
The pipes carrying water from the Strengbach River to the Riverlab machine at the outlet.
Video still Sonia Levy.

Fieldnotes from the Strengbach Critical Zone Observatory, Vosges forest, France, March 2020

Paul Floury makes me visit the Riverlab directly in the field at the Strengbach CZO this morning. He opens the door to a miniaturised and fully equipped chemistry laboratory. Pumps, tubes, computer: all the equipment needed to carry out geochemical analyses is there **(Fig.50)**. *The researcher set the machine going. It spits, groans, and begins to work. But the pressure is too high and the machine chokes. The river is indeed very heavy with sediment here, particles of matter that obstruct the tube that has been placed in the river to send the water into the Riverlab. The river doesn't make itself easy to monitor. After renewed attempts and by letting the coughing water tap run for several minutes, the measuring screen at last turns green. The noise and agitation are astonishing and contrast sharply with the other spots where scientists sample manually, calmly, and in silence. Bringing a fully equipped laboratory onto the site was not without technical problems.*

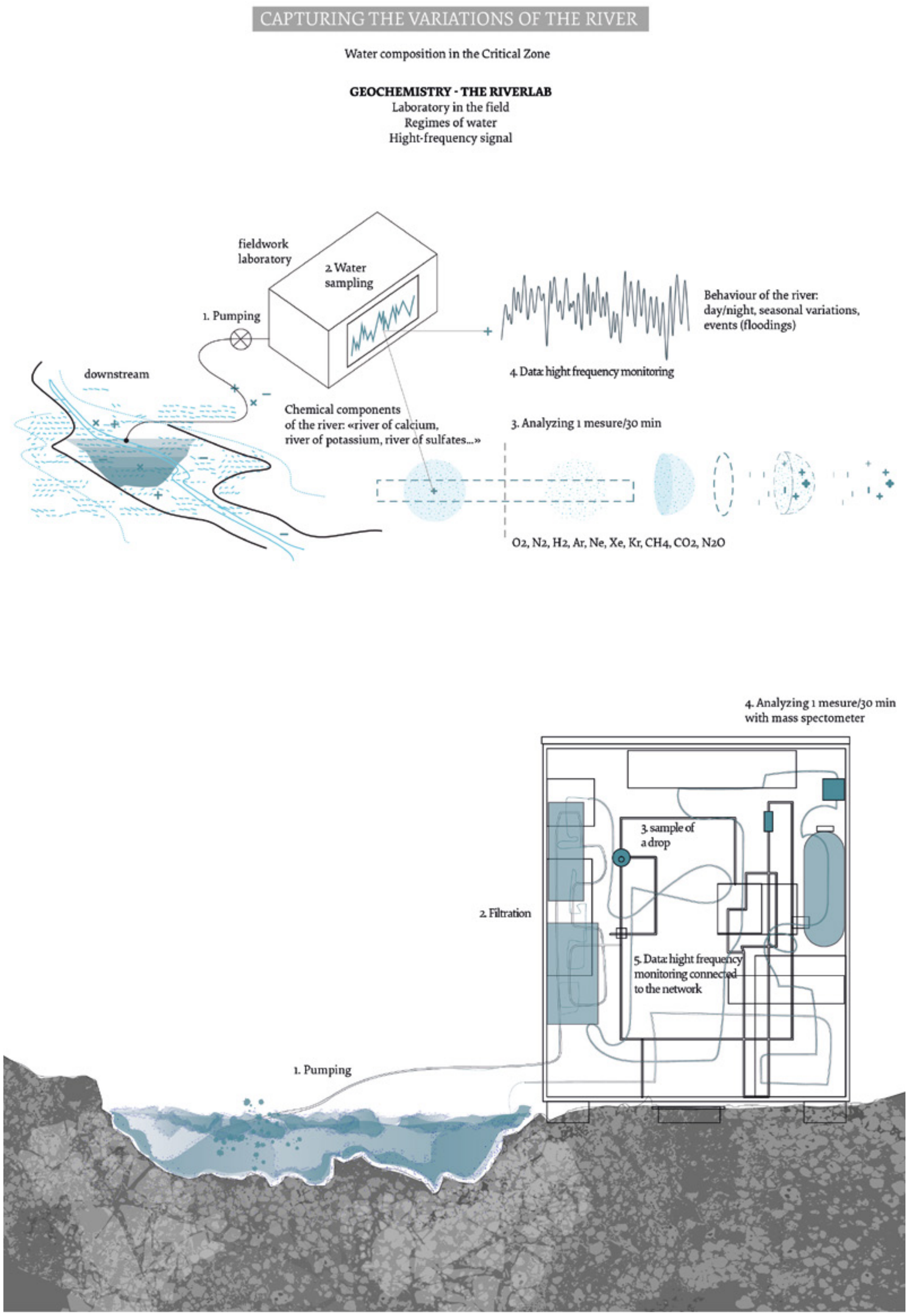

Fig.49. The Riverlab technique

Diagrams explaining the operating process of the Riverlab instrument. Drawing by the author.

Fig.50. Inside the Riverlab

The interior of the Riverlab. The Riverlab brings together the previously separate sampling, filtering and analysis practices. It shortens the time it takes to obtain data and saves space compared to the old laboratory where water is stored: here it passes through the tubes and is then released directly into the river without being modified. Photography by the author.

The Riverlab bridges the gap between the laboratory and the field. Sampling by hand is a slow activity and the most a scientist has ever done was every 7 hours. The Riverlab is capable of analysing all the chemical components of the river every 20 minutes! It measures the chemical composition by automatically taking water from the nearby stream **(Fig.51, 52)**.

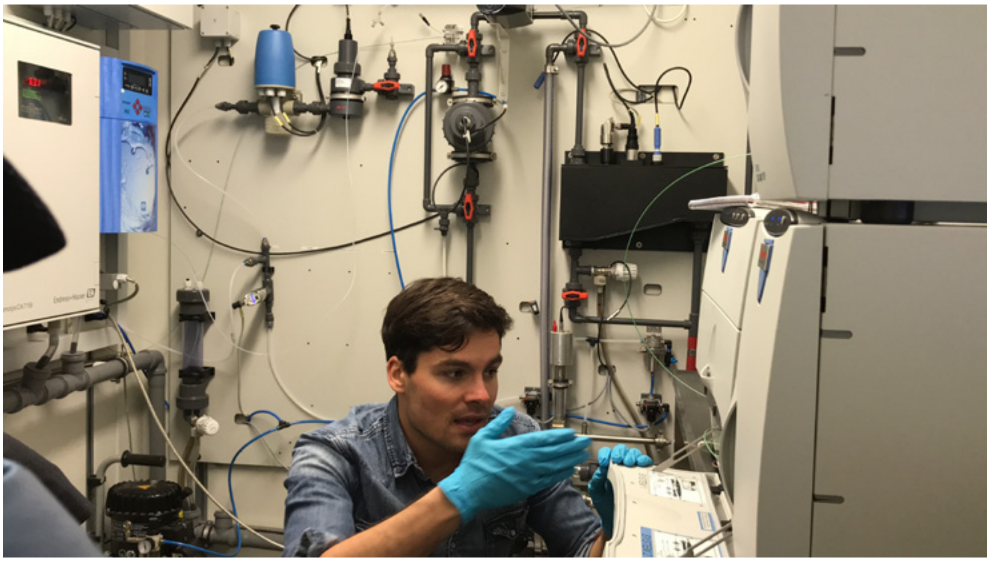

Fig.51. Scientist explaining the Riverlab technique
Paul Floury explaining how water passes through the machine. Video still Sonia Levy.

Fig.52. The instruments of the Riverlab
Small tubes feed the water into the high-sensitivity machine that analyses the chemical composition. Video still Sonia Levy.

Taking advantage of the fluidity of the water, the machine samples the river by letting the water flow through it. The machine works like a "cardiovascular system", with the river water constantly flowing through the machine at the same speed as it flows through the river. The Riverlab seeks to reduce short-sightedness by accelerating the rate of analysis. This leads to a thousand analyses per month of all the chemical elements in a river (Fig.53).

Fig.53. Records of data in the Riverlab
Records of the chemical composition of the water in the Riverlab. Video still Sonia Levy.

Inside the Riverlab of the Strengbach CZO with Paul, I get a chance to carry on the ethnographic field interviews. Paul tells me that he spent a lot of time inside the Riverlab last summer, every day during a month, and recalls some memories. Every day the same routine, and the progressive feeling "of being inside an organism with its own life regime, with a blood pressure to make it work, to stabilize the kidneys, which gets blocked if there are clots. Inside, the temperature must be maintained at 25°C and so with humidity, like a real human body." To assess his point, he makes me listen to every sound the machine makes: the pumps, the filter, the chromatograph, and every 5 minutes, an alarm that indicates that everything is working properly. Having been inside three different Riverlabs installed in three different CZOs for a long time (at Orgeval CZO, Brittany CZO and now Strengbach CZO), Paul can say that each of them has a different rhythm, that they emit different sounds. The Strengbach River is more 'pulsatile' or volatile, because the water regime of the Strengbach is more rapidly variable, as it is a small catchment area. At the Orgeval CZO, a catchment area ten times larger, the river is more stable, with less variation, and therefore with a slower heart rate. Thanks to the recursive nature of the sounds of the machine, and provided the ears are prepared, the scientist understands the scale of a landscape by the way the water enters the machine and how the machine reacts to the flow of water. The smaller the river, the more frequent the analyses must be because on a small river, the variations occur more quickly. Therefore, the rhythm of the analyses is adapted to the river's regime. The regime of a river is determined according to its flow speed. This flow rate also has an impact on the concentration of the chemical elements that react more or less intensely to it. This constitutes a wide range of hidden information that cannot be detected by monthly or weekly sampling. Continuous measurements of the Riverlab have thus revealed significant and irregular chemical oscillations between day and night, particularly during heat waves, to the point that researchers call these phenomena a "nychthematic concert" which appears to be constant, recursive. I share my thoughts about the Riverlab with Paul and Jérôme who join us in the field: the Riverlab seems to be a kind of temporal chemical microscope that enables the scientists to see all the variations of the river: seasonal variations, diurnal and nocturnal variations, one-off variations (floods). They agree and add that all these have different physical and chemical characteristics. To see them in real time is a major advance. These are the minute-by-minute rhythms, the pulsations of the water that runs through the heart of the Critical Zone and transforms it. Inside the Riverlab, however, the water is never visible as such. It appears as particles, molecules, shown by the graphs, the waves which the scientists know how to interpret. Form a non-scientist as me, it is pipes, valves, taps, test-tubes, and a computer. These rhythms, perceptible thanks to automatic high-frequency sampling, allow scientists to listen at any time to each element, each process, which, like the notes of a piece of music, allow them to recompose the "chemical symphony of the river". Overcoming short-sightedness, the Riverlab allows scientists to "temporally scan" the river's waters to discover new variations, such as the day/night oscillations of calcium, which are the "most tangible variations observed", and at the other end of the spectrum, the great rapid and abrupt variations that are floods. The Riverlab appears to be both a time microscope and a macrocosmic telescope. Then the analyses made by the Riverlab are sent and viewed live **(Fig.54)**.

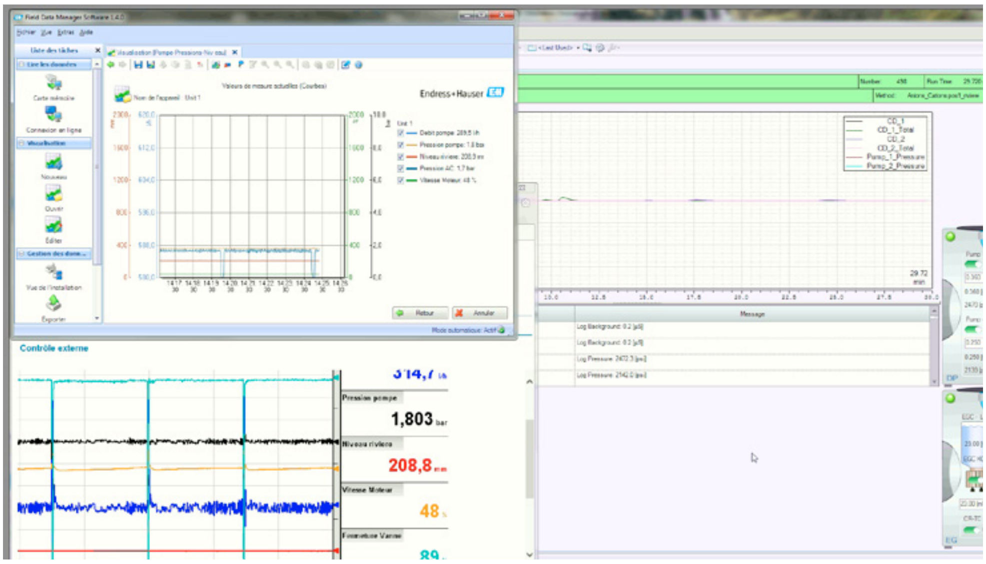

Fig.54. Creating a network of data
The recordings are sent live over the network. Using special software, Paul controls the Riverlab and can watch the data in real time. Paul Floury's screen shot.

Paul is also working to facilitate the exchange of data via a web platform where it is possible to find the data for each Riverlab. This platform is called Extralab. The Riverlab (the physical machine) and the Extralab (its virtual part) reconfigure the traditional link between the laboratory, a space housed in a building, and the field from which the data is extracted. "A riverlab is a concentrated laboratory," states Paul with conviction. This implies a change in the relationship between the field and the instrument. Most CZ instruments placed in the field do not send live data to the scientists' computers. The Riverlab does. Paul describes how the machine and the river form an intimate bond: "The idea is that this process is continuous, it is really the river that flows through the instrument. It's a new configuration for the instrument, it's not ''you import samples to the instrument', but it's the instrument that adjusts and adapts to the object of study. From the flowing water, we have the data in real time"[70]. This triggers a 'movement' through the landscape that is no longer seen from a distance. The Riverlab is usually the starting or arrival point of a CZO visit. The

70 Paul Floury, 2019.11.11

small architectural unit attracts and brings together scientists. According to Paul, the Riverlab offers a new proximity to the territory, and a new way of sharing science with the local population. His goal is for Riverlab to become a welcoming station used by multiple users: "What interests me is that we deconstruct the vision we had of the observatory where we brought back the sample we were interpreting. Here we delegate the instrumentation, we split up the laboratory, we digitize it in real time." Paul goes on further as defining the Riverlab as a little embassy for the Critical Zone:

> "The Riverlab is like a little embassy for all the research that is done locally, with people who will never come to a lab: farmers, schools, so it can become a mediator. We're relocating the laboratory, and it's also very new to be able to have local access to the advanced instruments we have at the IPGP, to observe the local environment. We reclaim the laboratory; we move it away. It's a scientific embassy for the laboratory, for the Critical Zone. I's a meeting place. Often, we camp around it during the day when we go on site. It's also the only place where you get a lot of different trades to live together locally, in the field, where they line up."[71]

The specificity of the instrument, its spatiality, gives it a special status that I had not witnessed before with other instruments seen in the CZ. The fact that it has an interior space blurs the previously defined boundaries between inside and outside. According to Paul, the Riverlab creates a new place where local high-tech science is carried out that goes beyond territorial presuppositions (what is rural is poor and access to science is reserved for the cities). Moreover, real time, which means that variations are captured without delay (the time it takes to return to the laboratory), increases the amount of data but also radically, conceptually and pragmatically changes the relationship with the landscape. The landscape is no longer a background where scientists go to extract something at a specific point, but it becomes a participant in the process of reading and extracting data. The way of observation, through mediators, through sensors, which extend our sensitivity, can change how the landscape

71 Paul Floury, 2019.11.11

is usually understood. This new sensor refines the relationship between the landscape and the laboratory in a new link that could be called a 'Land-Lab'.

Scientists sample the rivers by acupuncture. To analyse them, the laboratory is necessary, but it is too distant from the field, which prevents a good understanding of the infinite variations of rivers. The Riverlab makes it possible to bridge this gap. It becomes a river sensor, but also a space, a spatial sensor where the river acquires a new relationship with the lab. Conversely, this invention, this new instrumentation, deterritorialises the laboratory by bringing it in the field. Now that we have described the potentialities of this new instrument that captures the behaviour of rivers, what are the new properties we can discover with it?

5.3 Decomposing: from a river to a drop to a watershed

Thanks to the Riverlab, CZ scientists are able to decompose the river as it has never been done before to better understand it: it decomposes time, it decomposes water into drops and particles. This decomposition breaks down the unity of the river as we are used to seeing it, to bring a new understanding of river as pluri-elemental streams.

An instrument such as the Riverlab introduces new observation time scales called high frequency, which is in fact an extreme decomposition of time. Frequency refers to the rate at which an event evolves. A flood, for example, occurs within a few days or hours, whereas a hydrological season occurs on a year's scale. Geochemistry measures the concentration of chemical elements such as calcium or magnesium along long time series that show a trend, i.e. the general behaviour of an element at different frequencies. However, this understanding of trends is not sufficient to track variations in the elements, as we saw earlier. That is why the scientists want to increase the frequency at which the concentration of the elements can be measured, in order to acquire a signal that allows them to observe not only a seasonal cycle but also a daily pattern. Riverlab carries out this high-frequency observation which captures absolutely everything that could happen. This increase in the rate of observation raises questions about the way time is divided up. During the interview, Paul sketches while he talks to make me understand how the scientists understand time. He draws a line into brakes which he calls a ‘window’ (Fig.55). The conditions under which a measurement can be made, a phenomenon can be observed, is defined as a “time window”. It is a framework for observation that is limited by the time scales that a human being is capable of understanding.

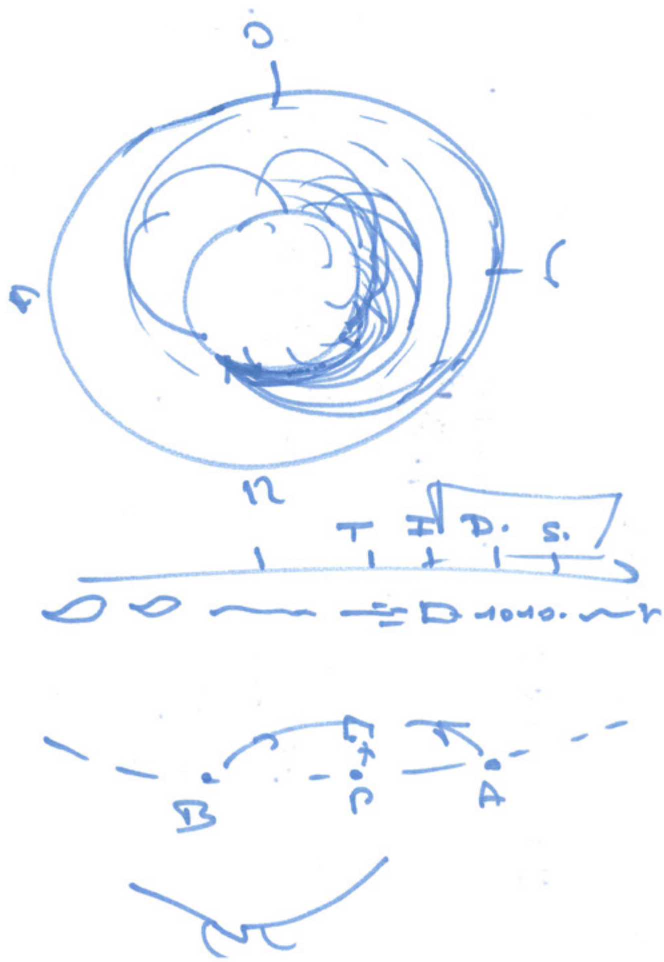

Fig.55. Time windows
Paul’s scheme explaining the concept of time windows.

Processes operate on different time scales, from the formation of geological layers on millennial time scales, to other processes that react annually, or daily, hourly, etc. This opens up a wide range of potentially observable frequencies and time scales. Therefore, any observation procedure must set limits. In the CZ, the time constraint is determined on the one hand by the period of time since an observatory has been measuring, depending on the age of the observatory from 50 years to 1 year, the so-called low frequencies, and on the other hand by the rate at which measurements can be taken (limited by logistics), the so-called high frequencies. Riverlab helps to open up the latter time window by extending the high-frequency measurements from daily to sub-hours. Therefore, time appears as a plastic, elastic and relative notion, depending on the phenomenon observed. If time windows are the framework for studying an entity and its composition, some entities are more difficult to observe because of their incommensurability with the time scale framing human activities such as political agendas or the daily rhythm of work, or even the span of a human lifetime. For example, the shape of clouds is volatile, stealthy and lasts a few hours. Some other cycles are too long to be perceived, such as the denudation of soil in a river basin. Each place is governed by its own process time scales, so each observatory needs to adapt its time window and set up long-term observations in order to "understand all the frequencies of the vibrations"[72]. The specificity of the Riverlab, which is entirely dedicated to the study of rivers, gives us a different understanding of what time and temporalities are. It does so by increasing the sampling and analysis of the elements that cross the river, by increasing the speed of capture of each tiny element that runs and elapses continuously.

A curious aspect of the Riverlab is that only a tiny part of the river is actually captured for chemical analysis by the machine, just a drop to be precise: "at the moment I analyse, every 20 or 30 minutes, the pipe tips over, gets stuck and the water is injected into the machine, but it's a very small volume of water, the injection loop contains micro-litres."[73] In the scientists' approach, a river is definitely not a line but... a drop, added to another drop, and so on **(Fig.56)**. In a single drop, there are no less than 10 to 15 elements. The Riverlab detects the chemical elements dissolved in a river. In a river can be found water, suspended matter, life, organic matter, bacteria, biotic and abiotic elements, etc. Riverlab deals with the inorganic part: calcium, magnesium, sulphate, chlorine, etc. that are dissolved. The molecular is therefore the extreme decomposition of matter. A litre of water is

72 Jérôme Gaillardet, 2019.09.18
73 Paul-Floury, 2019.11.11

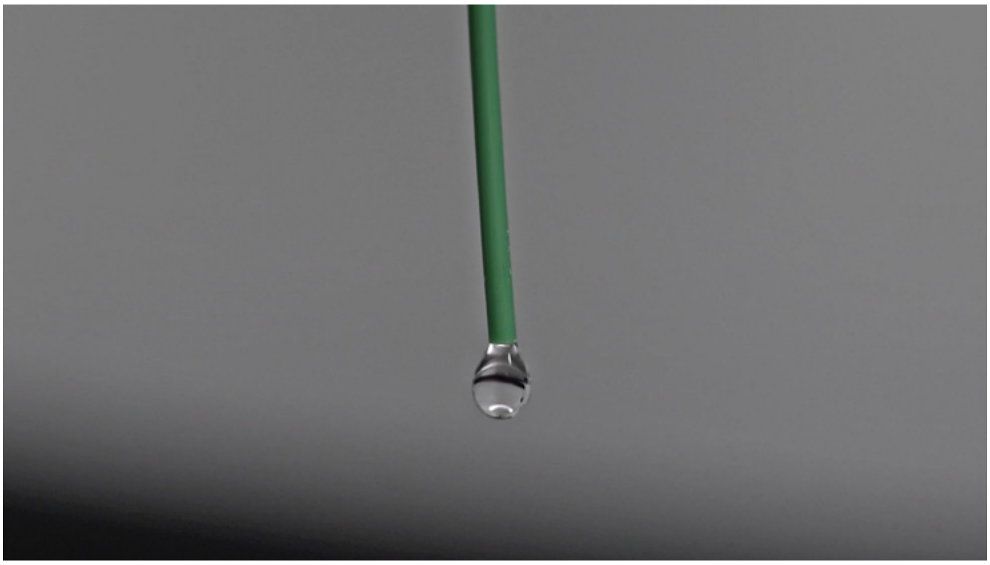

Fig.56. The drop being analysed
At the end of the filtering process, only one drop of water is analysed every 30 minutes. Video still Sonia Levy .

not a litre of H_2O, it is composed of much more: electrons associated to dissolved matter, chemical elements, moving in multiple directions. Geochemistry studies these combinations and their impact on the Critical Zone. Water is the first vehicle for these elements, i.e., it allows them to disperse in the Critical Zone. Calcium is a nutrient. Its presence is crucial to guarantee life. The chemical reaction of rainwater with rocks that dissolves millennia old limestone rocks and releases calcium occurs on multi-year time scales. Then, the particular hydrology of each place will determine whether the calcium will be transported, continuously or not, to the surface: the sponge in the ground swells or deflates. Each flood brings fresh water that is less charged and more aggressive to the rocks because it is out of balance with the chemistry of the rock. On the contrary, water that has been stagnant close to the rocks for many years will balance out, so this water will react less, and the scientists tell me that this water is therefore older and richer in calcium. Calcium, like magnesium and sulphate, are elements that come from deep geological layers, which is why they are very sensitive to variations in water, the “sponge” that is the soil. Other elements are insensitive to the sponge, such as chlorine or potassium. Therefore, each element tells its own story. Chlorine and potassium react more to the surface layers of the soil, and therefore to the anthropic disturbances that affect the surface. Potassium is not present in the soil, but it is present in plants and field crops due to the high use of fertilisers. Against all expectations, potassium is concentrated when it rains: the flow doubles its concentration, because it is charged by the passage through the surface layer. Paul is surprised by the Potassium behaviour: "potassium is really exotic! Its behaviour is crazy!" The Riverlab reveals the non-compliant behaviour of this element. "At noon, solar time, potassium rises a little earlier every day! So give me the potassium concentration and I'll tell you what time it is, it's a real sundial! But we don't know why it goes up and down!"[74] **(Fig.57)**

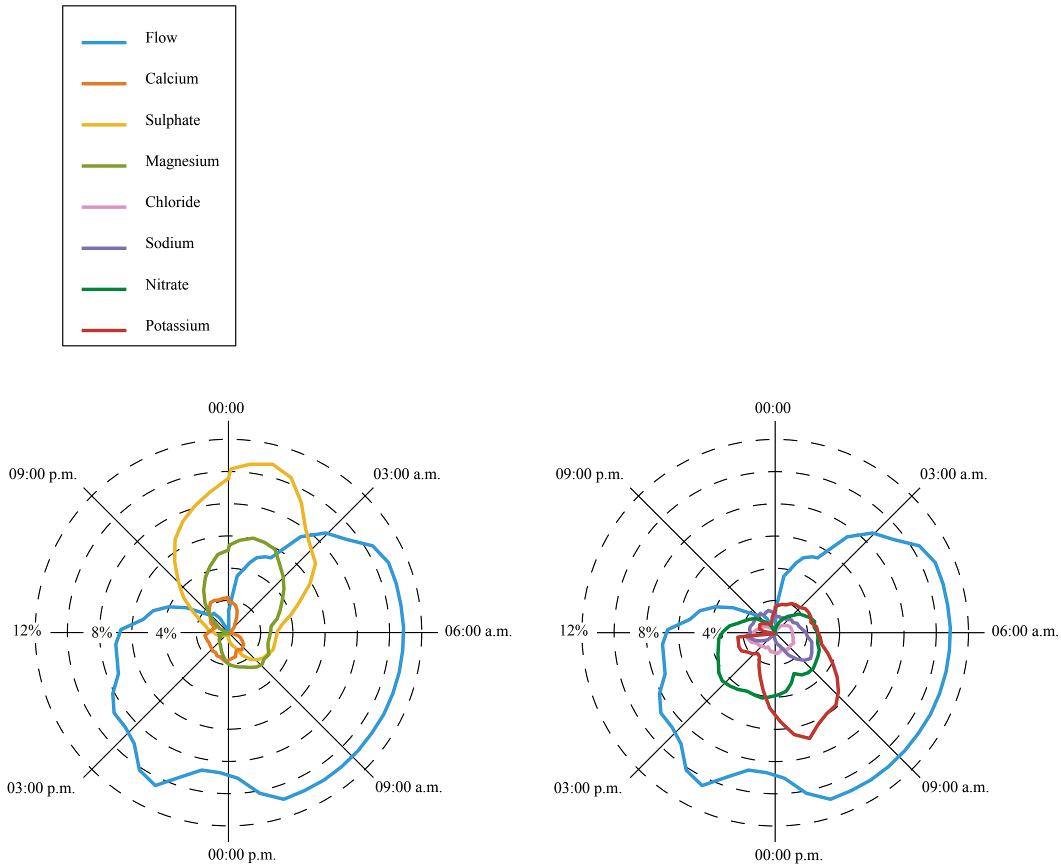

Fig.57. The daily variation of chemical elements

The chemical elements vary according to the time of day, while the flow of water is the same for each of them. Each element has its own rhythm. Some of them act as a sundial, such as Potassium which varies at noon. Graph by Paul Floury.

74 Paul-Floury, 2019.11.11

Other variations in the concentration of certain elements in river water are still unexplained, such as nitrate. Scientists see through the Riverlab that Nitrate explodes before the period of fertilizer spreading in the crops in November and January. But it also varies according to a day/night pattern that cannot be explained (Fig.58).

Figure 3

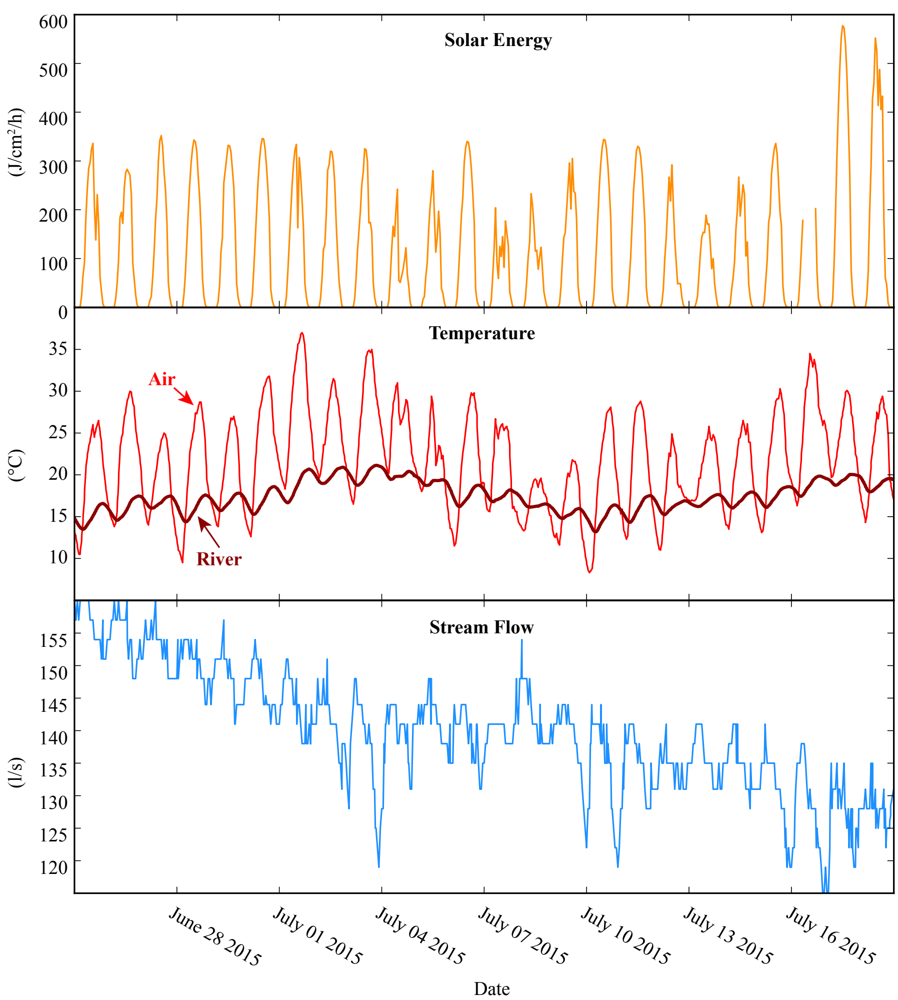

Fig.58. The annual variations of a river
Impact of solar energy on river temperature and flow in one month. Solar energy drives the water cycle. Graph by Paul Floury.

During hot summers when the flow rate varies, the nitrate concentration also varies, which could be due to the flow rate, which is related to air temperature, solar energy, which also varies every minute. Although the scale of the Riverlab analysis is microscopic (a drop), it provides information about a vast watershed. This calls into question not only time scales but also spatial scales. Moreover, these elements will all have their own line on the scientists' graph showing their variations over hours, days, weeks, months, years and so on **(Fig.59)**. It is no longer a single flow line that is observed, but elementary timelines. The traditional graphic representations of a river as a line on the map, in conventional cartographies, is limiting, compared to what these behaviours and timelines suggest. The Riverlab quantifies each element in grams per second (concentration). At the CZO Orgeval for example, Paul reports that 32 kg of calcium escapes from the river every day. It is as if there were 32 kg of rock flowing down the river. Of course, they are actually dissolved, which is why they can't be seen. But this represents a large quantity. And it's the same for potassium, nitrate, and so on. So, instead of just a river of water, the scientist actually sees many "rivers" of elements: "You have to get the idea of a river of calcium. It is in dissolved form, the water carries it, but it is a river of calcium. So there are elemental rivers of elemental flows."[75] From the words of the scientist, there isn't just one river (water), but there are as many rivers as there are chemical elements. The world opens up to a complexity that is difficult to grasp. Water, considered as one of the most identifiable entities of the Western landscape, becomes the least assignable to an identity. The scientific term is "elementary flows". Extending it to the entire Critical Zone, Paul adds that "there is a potassium watershed, a calcium watershed, just as there is a water watershed."[76] Similarly, there are calcium floods, and other elementary floods. And these floods of elements can be as threatening as those of water. For example, floods of nitrates cause algal invasions at the estuaries. The aim of the CZ scientists is to reconstruct and compare the behaviour of elementary floods, however varied they may be. Graphs are made to observe each behaviour and determine how each elementary cycle contributes to the CZ. They were thus able to reconstruct the vertical distribution of the elements: potassium being at the surface, calcium throughout the vertical section on the CZ, and Sulphate being present at depth. Just as there are flows of elements that flow, there are flows of elements that fall, that come from the atmosphere, in particles: "this is important because it redefines the contours of the Critical Zone. Some grams of elements become dust in the clouds

75 Paul-Floury, 2019.11.11
76 Idem

and fall as rain."[77] As a consequence and to perform a play on word with William James who coined the term pluriverse, the Critical Zone is a plu-rivers: there is not one river but a plurality of rivers. The river is a pluriverse which shouldn't be reduced to a bounded entity. It has multiple regimes, dimensions, qualities, which 'overflow' the traditional understanding of what a river is.

In order to follow the variations in rivers, scientists have to decompose the river components. The speed-up of sampling requires the decomposition of how we think about rivers, by setting up a new frame of reference: high frequency, which divides time into numerous sequences. This decomposition explodes the unity of what we used to think of as a river, or rather duplicates, multiplies that which was one. The scientists decompose the river to a drop, but astonishingly, this drop is a condensate of the river, bringing together all the elements that make up the water and which are decomposed, made visible by the small geochemistry lab inside the Riverlab. Each element generates its own story in the Critical Zone. Finally, there is not one river but several elementary rivers with different flows whose profiles cannot be superimposed. So how do scientists make sense of this complexity? How can rivers be re-traced?

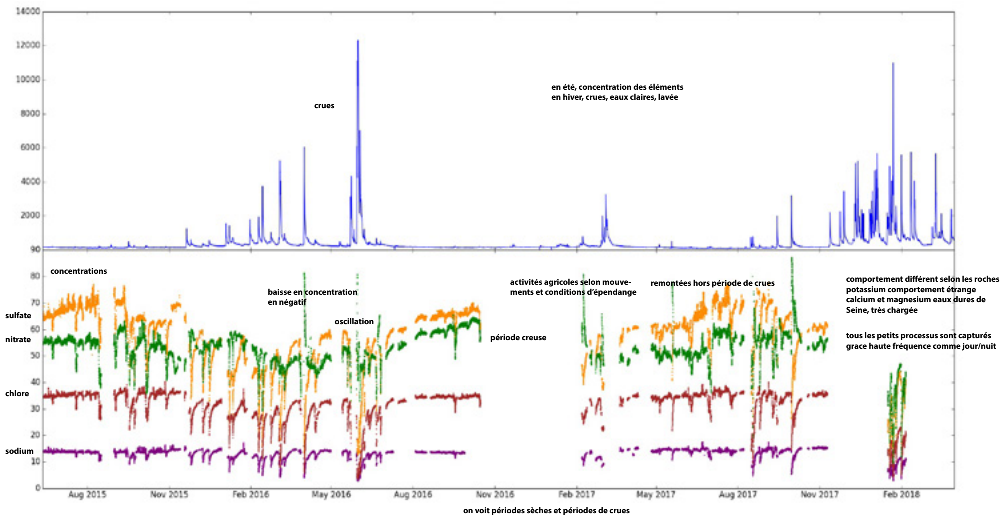

Fig.59. Graphs showing variations over 3 years

The scientists produce graphs that show the results over time. Here is a graph drawn by Paul to which I added comments during his interview.

77 Paul-Floury, 2019.11.11

5.4 Tracing: the paths and ages of water

The Riverlab studies the composition of the river, but in the Critical Zone, the scientists also trace the whole water cycle and water paths to answer critical issues such as resources. The scientists follow, trace the water through the layers of the CZ. In the atmosphere, water is seen as waves through the instruments. At the surface, the analysis shows multiple flows. At depth, it is not a static water table but an entity that ages and fossilises. Following its paths outside the watershed unit of observation, the scientists face the problem of scales.

The amount of water contained in a fall of rain does not fall to the ground once at the same time. It is more like a wave, an undulation. The Gravimeter, the same instrument we saw in last chapter, is able to see the imprint of this wave afterwards as rain changes the gravity of a territory. Jacques Hinderer in his office in Strasbourg shows me this wave on his screen, another line added to the tide's gravity: "here he can see an effect on gravity with a slightly decreasing energy cycle that could be related to evapotranspiration. When water from trees is drawn towards the earth, gravity within the Strengbach CZO watershed increases. Then it decreases again due to evapotranspiration with another cycle." When it hits the ground, not all waves of rainwater fall in the same way either. Some of it will actually flow into the river, but some will "pull back, isolate itself, weigh itself down and continue"[78], because it will have its own behaviour and its own path on the surface of the ground. Another part will sink deeper, infiltrate and later burst out, but when and how much are still misunderstood. Rainwater is therefore taken as a wave in the CZ, which shrinks, ages, until it fades away. When the rains are intense, they cannot infiltrate the soil, so the water rushes downstream, feeding the river. Flooding occurs when this flow exceeds the river's capacity to contain it. A natural river is larger than limits between soil and water, as tragic floods remind us when dams, banks, give way under the force of river flow. Scientists refer to the river in terms of speed and cycles to avoid reducing it to a stream of water. Indeed, there are not only water floods but also chemical flows. Their impacts should be separated from water flood phenomena with likewise dramatic impacts such as transport of nitrate to

78 Jacques Hinderer, 2020.01.17

the ocean causing asphyxiation of coastlines by algae. But these chemical phenomena are hard to predict. Indeed, they don't vary according to the flow stream, but to their chemical properties. Traditionally, floods are described as a flash, a moment, and we tend to think that the river comes back to the level it had before the flood. Potamologists like Jérôme Gaillardet and his team at the IPGP, record different variables and tell me that the rise of the flood is not the fall of the flood. In the Orgeval CZO, the flow rises sharply but falls very slowly. Scientists don't observe the same phenomena when they look at the rise of the flood or the fall of the flood. It is called flood twice, with the same word, but they are not the same phenomena. "It is the same event, but the rise is not equivalent to the fall. Moreover, the nth flood of the year remembers the n-10th flood. There is a kind of legacy, a heritage."[79] Jérôme suggests that "each flood has the memory of the flood before it", each flood is influenced by the last one, and therefore nothing can predict that a flood this year will have the same tendency as the next one next year. Floods accumulate, they are not singular events. How do the scientists understand this legacy? How do they access the "memory" of the landscape?

> Fieldnotes from the Strengbach CZO, Vosges Mountain, Eastern France, July 2019
> *I follow the scientists at the Spring station in the middle of the Strengbach CZO. They open a cast iron hatch in the floor* **(Fig.60)**. *Four sources are flowing from different depths in a cavernous underground concrete chamber nested in the middle of the watershed* **(Fig.61)**. *Marie-Claire Pierret measures the flow and temperature of the four springs which are merging here to supply the village of Aubure down in the valley. In summer, the temperature difference between the springs is significant, since some flow out at the surface and hence are heated by the sun, whereas others are protected in the depths of the Critical Zone. In the spring there is almost no temperature gap. Marie-Claire adds that each spring has its own chemical composition because they take different paths in the ground before reaching the water table and the spring at the surface at different times.*

79 Jérôme Gaillardet, 2019.09.18

Fig.60. Outside the source

The source station at the CZO Strengbach. The spring is located in the middle of the watershed. It is managed by the village, which has given access to the scientists to carry out analyses. Video still Sonia Levy.

Fig.61. Inside the source

Inside the dark underground chamber that houses the source, the scientists measure the temperatures of the four springs that gush out at different depths. They form the flow of the stream that runs to the surface from this point. Video still Sonia Levy.

The CZ is the zone where water infiltrates, is stored and purified. Scientists investigate where there is storage capacity, where the aquifer is thick and porous, often around springs. Springs exist before villages have been settled. If they disappeared, whole villages would become extinct. Thus, in every CZO near urban centres, springs are monitored. In the cities, the tendency is to forget these hidden infrastructures, as well as the aquifer that sustains them. Aquifers are underground and invisible, sometimes so thin that their presence is difficult to feel. The role of gravimeters is now to detect this small groundwater signal. Sometimes the water below is so little that we cannot see it unless we have a very sensitive instrument. On his screen connected to the gravimeter, Jacques analyses the data by subtracting the intense events that mask this thin layer of water: “I remove the tidal effect, I remove the effect of atmospheric pressure, I remove the linear drift. Once I do all this, I can have a small gravity signal that is linked to the water table”[80]. The hydrological signal is linked to the evolution of groundwater under the watershed. This signal seems insignificant compared to other signals such as tides. In fact, continues Jacques, “the hydrological signal represents less than one hundredth of the total gravitational signal, and is therefore invisible without any corrections”. Taking care of the CZ also means learning to hear the whispers of ghost water. In the CZO Strengbach, beneath the impressive Vosges mountains, the water level, which is the total stored water, is only about 25 centimetres. I exclaim that is very few. Jacques agrees, it’s not a lot... But he tempers: “if the medium is porous, for example 10%, that is to say if there is 10% pore volume in the matrix, then the 25cm becomes a 2.5m buffer zone where water can be found.”[81] The nature of soils is thus as important as the quantity of water. The surface layer of the Critical Zone is averagely porous, that is to say, it allows a middling amount of water to pass; the trees are very porous, the air even more so, while rock has low porosity, but can be fractured – that is to say, split from the inside by a continuous flow of a stream of water that alters the chemistry of the rock and reduces its density. Water can also be captured in pockets or come out suddenly through ‘macropores’, like some tubes, opened up by mammalian activity or the decomposition of a root. This granularity, or variations of porosity, conditions

80 Jacques Hinderer, 2020.01.17
81 Jacques Hinderer, 2020.01.17

where the water flows. In the Strengbach CZO, the water pathways from the raindrop to the spring cross the soil and pass through the fractures of the granitic bedrock. The soil here is porous: it is the groundwater recharge area which is threatened by increasingly frequent periods of drought. Water flow paths are among the most challenging aspects of the Critical Zone to observe, model, and understand. Yet this is crucial for the management of our water supplies. Water paths follow currents, as in the ocean, depending on the porosity of the Critical Zone. In Guadeloupe CZO, the objective of the intensive measurement campaign that the scientists have undertaken in May 2019, is to validate a hypothesis concerning the trajectories of water flows at depth: does the particular volcanic topography (called knickpoint, which means a shift in the geomorphic structure) of the island control the water trajectories and therefore their chemistry? **(Fig.62)**

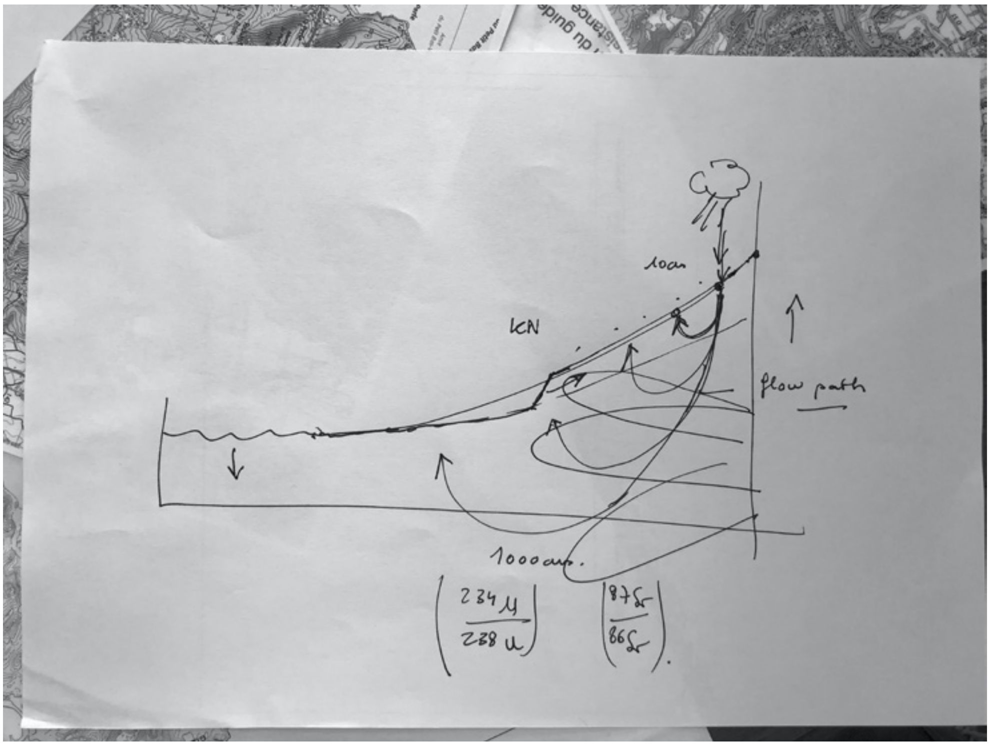

Fig.62. Drawing of water's ages
Diagram showing how groundwater is a distribution of ages. A raindrop falling on the surface infiltrates at different depths and can stay from a few days to thousands of years inside the rocks before coming to the surface. Drawing by Jérôme Gaillardet

This will inform models such as those Sylvain Kuppel, a postodoc working on the CZ, aims to understand the relationships between chemistry and water paths: "chemical weathering reactions can depend on how long the water remains in a given place. Water is a medium for the geochemistry of the CZ."[82] Complementary to the work of Sylvain, Jean Marçais is also working on models focusing on the physics of the water paths. He is based at the IPGP but works with several CZOs. He reconstructs how the water passes at depth **(Fig.63)**. On average, a drop of water remains in the Strengbach catchment for 30 months before coming out again, but this varies from one observatory and one part of the world to another. In Guadeloupe, scientists suspect that infiltrated water stays much longer. Therefore, water has different ages! Some waters are even termed "fossil" because they remain stuck deep in the rocks for hundreds of years. But why do water paths influence the chemistry? How does a spatial trajectory come to change the composition of water? This water at depth, which has sometimes altered the rocks into sand, is ancient, "fossilised", and rich in minerals at these depths. In the fractures, the water can remain for many years, even decades. But not all the water falling from the rain will be absorbed underground. Depending on topography, soil composition and flow, some drops will reach the bottom of the hill directly, some will infiltrate and gush out a few days later, and some will infiltrate deeper and stay longer. It is not yet known which paths the different underground flows take, and much effort is being made to understand why the flows follow this or that path in the soil and thus cause the release of the chemical elements that feed the biosphere (trees take the elements from the rocks through their roots). We are accustomed to the ages of the trees that we can read through the rings of the trunk. We are accustomed to the ages of organisms that we can read through the cellular organisation. For CZ scientists, the age of water is also important. Paul has to take it into consideration when analysing and explaining the results of the Riverlab: "water flowing in a river does not have an age but a distribution of ages. Age 0 starts with the first drops that touches the ground, the life expectancy of a cloud is 10 days, the older the water is out of contact with the atmosphere, isolated, sequestered, the more it will

82 Sylvain Kuppel, 2020.04.08, remote interview

have a certain dissolved gas signature due to radioactive elements that will decrease"[83]. When it rains, scientists observe an age distribution in the river that they call TTD for Transition Time Distribution: "Some of the water is a week old, some is a year old, and a thin trickle might be even older."[84] The chemistry of this old persistent residual water is different, it carries the history of the depths. It is through these measurements that scientists are able to trace the ages of the water. The same water from a watershed has several ages, as does our body: "I myself am 30 years old, but I am not really 30 years old, most of my cells are less than 7 years old, 1 year old, etc, we are ourselves a transition of ages."[85] Therefore, the CZ is a distribution of ages. It multiplies even further what water is: drops, chemicals, with many time scales and many different ages. Each territory is an infinite superposition of ages not only because of its geology (rocks) but also because of its waters.

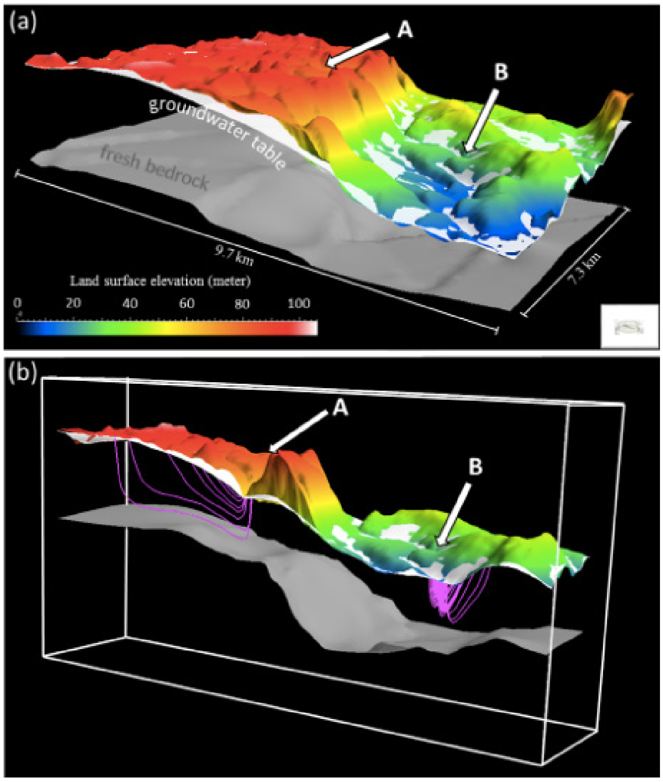

Fig.63. Reconstitution of flowpaths

3D modelling of deep water circulation in relation to topography at the Brittany CZO. Image by Jean Marçais presenting his work at the OZCAR virtual days in 2021.

83 Paul-Floury, 2019.11.11
84 idem
85 idem

The depth at which water can be found is considered the lower limit of the CZ by most scientists, but this depth is not constant everywhere. Horizontally, the boundary of the observation is set by the watershed, a useful unity in order to circumscribe the area to be monitored. However, this geographical unit doesn't explain CZ processes.

First, because watersheds are nested: a watershed is included in a larger one and so on. Some CZO are a complex assemblage of several watersheds (such as the Amazon CZO) whereas some are simple (such as the Strengbach CZO)–The complexity of nested watersheds is that they extend processes within each other without necessarily being able to simply add them up from one basin to another. Second, a huge phenomenon such as a river flow occurring over few meters wide, may fade away completely in the face of another small phenomenon but homogeneous such as the groundwater table influences over kilometres squares. There are no necessary correlations between scales and phenomenon force. Third, a CZO is a system where phenomena escape full understanding because the cycles are open. Paul explains that a significant part of the water that falls evaporates immediately, another part infiltrates and another part escapes. As a result, the river outlet represents only 10% of the total amount of water that has fallen on the watershed area. Scientists are only able to capture a fragment of the river's signal, a play of interaction between rain and river and their ages. Observation consists of intercepting the element with an instrument. It is a time lapse that gives a local measurement to a cycle. But the whole signal is simply impossible to measure by empirical means. This is because water, and thus all the elements it carries, 'leak outwards'. "We cannot close the amount of energy recorded in a day/night cycle because we don't know how it dissipates at the watershed scale. Some of it is related to bio, some of it is related to evapotranspiration, and it's repeated every day. But it's leaking, the river is leaking, the bio is leaking etc."[86] Phenomena escape the possibility of observation precisely because they are connected. Therefore, at the scale of an observatory, whether nested or simple, the cycle of the process does not come full circle. Water and all the elements and sediments it carries will leave the observatories via rivers to reach

86 Paul, IPGP 2017.07.17

the ocean, and the observation of the cycle of this element can therefore never be 'complete'. In a CZO, a location is not an enclosed space. It is rather what leaks, what is open. This defines the boundaries of a territory differently. Indeed, on a global scale, there is a loop, a cycle is closed, but not on a local scale. This reverses the relationship between the local and the global. On the contrary, the limited boundaries within which 'local' places seem to be enclosed, are, from a biogeochemical point of view, totally open, in motion. The more a territory is small, the more open and permeable it is consequently. Recently, Jerome defined the global as a boundary condition: "I became aware that Critical Zones are local places and that our problem is not global. Global is a boundary condition: CO_2 is global, warming is global, plate tectonics are global, but these are boundary conditions for us. How our Critical Zone evolves there depends on the conjunction of local parameters."[87] The larger a territory is, the more it is consequently closed and does not leak, the Earth being the ultimate closed space.

The new understanding of a plurality of rivers affects the different layers of the CZ, from the canopy to the deep rocks. Water triggers an effect on the Earth's gravity. At the surface, scientists observe different behaviours when water hits the ground: delays, memories, dilution, desynchronisation. At depth, water ages and becomes fossilised. Finally, it escapes the boundaries of the Critical Zone Observatory, flows beyond the watershed and connects to other watersheds.

87 Jérôme Gaillardet, 2019.09.18

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5.5 Connecting: a set of signatures

By decomposing a river into drops, multiplying its flows, expending its territory through the depths and even exploding the geographical unit of the watershed, scientists see water as geochemical molecules. They aim at understanding how these molecules behave with each other and how they disturb environments or not. The river is no longer seen as a line sectioning a dry land. It is not even a flow that geochemists see but a medium through which they access the understanding of cycles. The cycles are a reconstruction of each elementary trajectory, flow, through the different compartments of the CZ. Water is a means of transport for these elements (nitrate, calcium, potassium, carbon, etc.). In this approach, water is a connecting entity.

What interest the scientists is to understand if chemical cycles are correlated or not. Correlate means: when one element is linked to another and co-varies. Therefore, measuring one is measuring the other, as a proxy for several others. Each element 'plays' or 'moves' in its own way. Scientists must first decompose these different behaviours, as we saw in the section 'Decomposing', and then decode the patterns, similarities or dissonances. Thanks to the Riverlab, the scientists are able to compose a matrix of the elements measured in Orgeval CZO over a period of one year **(Fig.64)**.

> "This matrix, figure, shows the measured concentration of each of the elements vertically and horizontally. One element is reported in relation to another. For example, calcium is reported as a function of sulphate, etc. We look at the correlations. The different colours are the different floods and events. For example, we can see that nitrate is never correlated with chloride"[88].

88 Jérôme Gaillardet, 2019.09.18

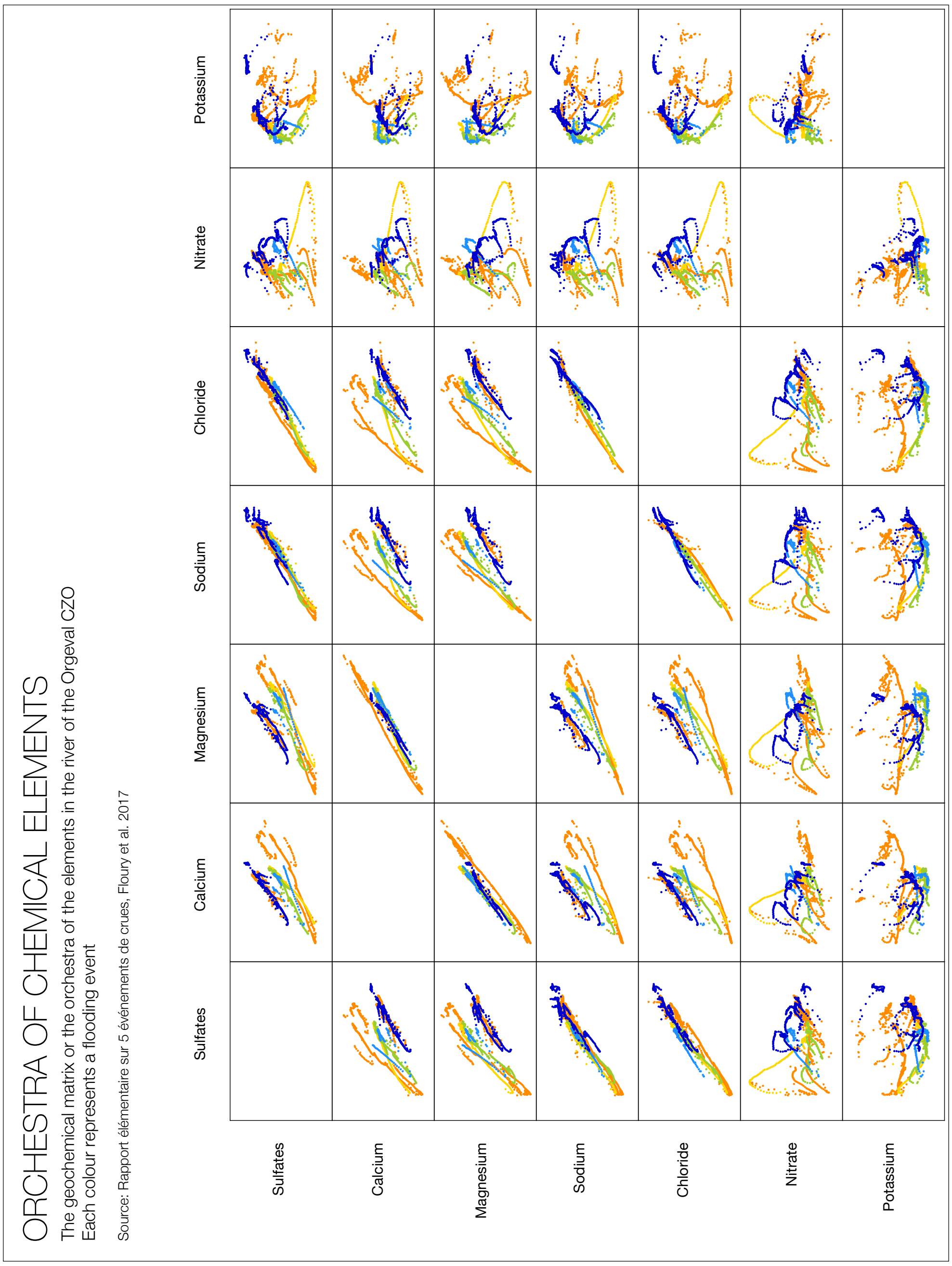

Fig.64. The Riverlab Orchestra

Table of chemical elements in the river at the Orgeval CZO. The data acquired by the Riverlab and analysed by the scientists show how certain elements are correlated (co-variables) with others or not during different flood events (represented by different colours). The geochemists refer to this as a musical composition where each element is an instrument playing its own melody. Diagram Paul Floury.

Their trajectories do not coincide. Jérôme and Paul are written an article on these results. They compare this matrix of distribution of elements to a musical score, a symphony where the different chemical elements would be musical instruments playing together or not: “Perhaps an element is actually an instrument. The sodium instrument plays the same note as the sulphate instrument”, says Jérôme. Paul goes further. Remember what he said about sampling water at the rate of manual samples: it’s like listening to a note every minute. Now the Riverlab provides him with a data set tight enough to be able to listen to the river “symphony” continuously. Turning these data points into sound in his scientific software called ‘python’, he creates a code to generate a sound signature for each of the elements that varies daily, seasonally or during floods! **(Fig.65)**

> “I made a small sound creation with the data of the sulphate over one year, each note corresponds to a chemical element and according to its value to a more or less high note. The volume represents the flow, more or less powerful. If there is a huge flood, the sound is very loud, if there is a small trickle, it’s a low sound. I can recognise a watershed by the measurements. I see grams per second, my eyes see elementary flows, but I could also hear the nitrate locally. I called it a ‘potamo symphony’.”[89]

The river as a composition of elements cannot be heard with the sound of flowing water, as we traditionally know it. Instead, it is a totally surprising sound that I hear on Paul’s computer, close to a contemporary music score that follows the variations of river and its chemicals. We do not hear a uniform or steady sound, but rather many ascents and descents, layered notes and complex arrangements.

89 Paul-Floury, 2019.11.11

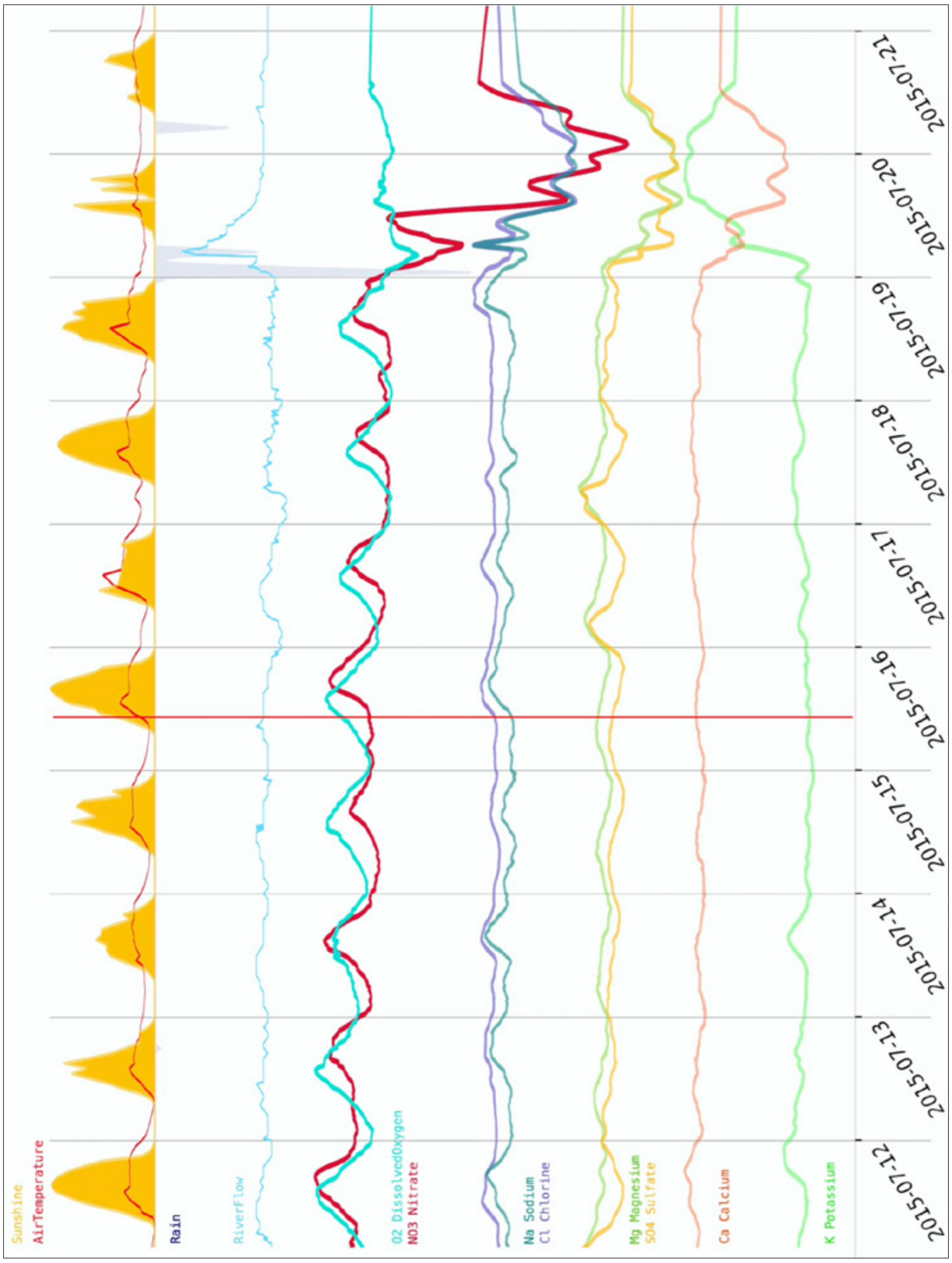

Fig.65. The music score of the river!

The data from the graph on the left, acquired by the RIverlab at the CZO in Orgeval, was transformed into a real musical composition by a composer for an art exhibition on the critical zone at the ZKM centre for art and media in Karlsruhe, Germany. Image and sound: Grégoire Lorieux, in collaboration with Paul Floury, the Riverlab geochemist, commissioned by Alexandra Arènes and Soheil Hajmirbaba for the installation Critical Zone Observatory Space, 2020.

Thanks to high-frequency monitoring, scientists are able to record precisely how the soil reacts to fertilisers and how these chemicals will be released excessively into the river or absorbed by the soil. During a flood at the Orgeval CZO, they have measured that the nitrate concentration in the water doubles: around 100 extra nitrate escapes through the river. The leaching of fertilisers is very high during a flash flood: it represents tons per day that leak and spill into the estuary, causing eutrophication downstream. Potassium, unlike most elements, is concentrated during a flood because it is found in the surface layers. Potassium is not correlated with anything, but it is very present in fertilisers. This means that at a certain time of the year, humans inject a lot of it into the system. So the elements are distributed along a vertical line, some are more present on the surface and other deeper down and variate because of water paths. Depending on the level of the water table, a flood will be felt differently. If it hasn't rained for a long time, the water table is low and the elements will therefore be more present at depth. On the contrary, in the winter, when it has rained a lot, the water quickly saturates on the surface, so that it contains more elements on this layer. Many dynamics have to be understood according to the surface, the depth, the mixing during floods. Phosphate has yet another story. It is extracted in quarries from the rocks and then used as a fertiliser for crops. When it is spread on the soil, it changes the soil's composition. These patterns of each chemical element are called "signatures". In the laboratory, the work of geochemists consists of "extracting signatures", i.e. producing visualisations of the functioning of certain types of variables. Sylvain K., the scientist in charge of modelling the Critical Zone, explains that signatures are actually a kind of preferential relationship between two or more things, phenomena or elements:

> "Signatures are a bit like how one connects with the other or how storage connects with its own change. Indeed, the term signature is a bit vague, it can be seen as a quantity, a scalar, a number, like how long it takes for the water in a watershed to go down after a peak flow. For me it can also be the form of a relationship: its slope,

or if it cycles."[90]

The signature is therefore the form of a relationship, connecting two or more notions or phenomena. These signatures are important to understand as they reveal how cycles are disturbed. Scientists establish the cycles to understand local phenomena and especially the involvement of human activities that put pressure on these cycles. Cycles are characterised by a certain regularity, at least a movement that can be understood by its recursivity, as in the case of sulphate and magnesium. But scientists' observations show disturbances in the cycles: "The anthropic impact of intensive agriculture has strongly affected water chemistry, the supply of fertilisers: potassium, nitrate, chlorine, and sodium with livestock farming, all of which contribute to the degradation of water"[91]. In Brittany, for example, at the Ploemeur CZO, scientists are monitoring the residence time of nitrates in the CZ. Human activities have completely disrupted this cycle. Indeed, Jérôme explains that humans have generated this cycle that did not exist before. It is a small cycle, the passage from nitrogen gas, which is a huge reservoir, to organic nitrate. This flow did not exist 150 years ago, but today it is very high. Humans appear as a cycle changer, a diverter of cycles, they even create new ones, or accelerate the flows in the most Critical Zone for life. In the Orgeval CZO (Ile de France near Paris), the water is polluted by the fertilisers used to increase crops production. The city water authorities have to take industrial type action to clean the nitrates for drinking water. But it randomly does this because it does not know the composition of each water source, where it comes from and where it goes before it is collected for drinking water supply. If it were possible to know which streams contain the most nitrates, this could help to better target denitrification techniques. Geochemists know that the presence of sulphate contributes to denitrification and they can measure the sulphate content of the water, enabling them to tell where the water contains the most nitrate. Scientists are everywhere confronted with the presence of human activities in the CZ, through the chemical traces they bring with them. The Critical Zone appears indeed to be the zone where the cycles are disrupted. Thus, it is as if human decisions

90 Sylvain Kuppel, 2020.04.08
91 Paul Floury, 2019.11.11

were imprinted on the tiny geochemical elements that scientists decompose and more work is needed to acknowledge these connections. Paul explains: “Imagine that there is a pollution like Lubrizol or Chernobyl. To understand the impact is to grasp when, how much and for how long the pollution is going to be. If the dilution is strong, like in Fukushima, in the surrounding rivers, or in Chernobyl, the impact will not have the same effect if the aquifer is recharged or not and will therefore contribute or not. If we had a concentration of uranium, we would see that in the month of June we would be much more impacted. For that, we need to follow the same element over the months of a year.”[92] Here, risk is understood not only as an event, but also as a long-term structural effect on the CZ. They shape another territory in the long term. To summarize, we have seen in this part that rivers are tracers of cycles, which themselves transform landscapes. From the point of view of CZ scientists, water is a sensor-sentinel of the chemical elements and their trajectories that generate global terrestrial cycles. The scientists study the correlation between the cycles, i.e. how the rhythms of the different cycles adjust together or not. These cycles can be strongly disturbed by humans (disconnection, decorrelation, bifurcation) whose activities can be traced biogeochemically.

92 Paul Floury, 2019.11.11

5.6 Conclusion: the many rivers of elements, a 'plu-rivers'!

Monitoring the river calls into question the scientific practices we saw in the chapter on soil, the field/laboratory relationship, and their spatial and temporal rhythms. The 'myopia' when observing water is not due to a limitation in seeing visible matter as in the soil observation, but because of interruptions in temporal series of measurements. To overcome it, scientists are developing a sophisticated instrument that can sample all the chemical elements in a river in real time. This is the Riverlab, a kind of outdoor laboratory that analyses chemistry in a way that has never been done before, opening up windows of time and increasing the scientists' ability to observe. The Riverlab changes the definition of territory, the Riverlab becoming an ambassador of the CZ, a place where territory and science can meet. It redefines relationships in the landscape as a place where scientists are part of, so there is no longer a background to sample and extract. With this instrument, we witness the agency of the river, which is no longer a passive décor in landscape. The Riverlab allows scientists to follow the multiple rhythms of rivers, opening up a new and unthought-out world, the cosmology of the river, adding new properties to the river. The observation time of the river is crucial to reveal these properties: the increase in the rate of observation conditions the possibility of decomposing every drop of water from the river in the Riverlab. And it is this possibility of decomposition that conditions a new way of understanding the river: there is not just one river but as many rivers as there are chemical elements that behave according to their own history and interaction with the soil, solar energy, or human activities. Therefore, we should not see a river as a single flow of water but with as many flows of elements, each of which varies according to its own pattern. The cosmology of the river is a pluriverse. As a consequence, it puts in question our understanding of river in a design project. As designers don't have this riverlab instrument, we reduce the river to a flow through the city and design its shore only according to this flow, but there are many other dimensions, chemical dimensions, that inform what happens on a territory which could be included to renew and enrich river designing. Where the water is located is a crucial question. In this chapter, we followed the scientists who trace the water through the different parts of the CZ. We used to think of the river as a constant flow that can be disrupted by a sudden event. Careful monitoring of the river reveals a more complex behaviour. Groundwater or rain waves modify the gravity. On the surface, their chemostasis and memory make rivers unpredictable. At depth, water flow paths break the unity of rivers and define them instead as a distribution of superimposed ages. Only a very sensitive instrument detects the very thin and ghostly layer of the water resource. The scale of a phenomenon may be different from the scale of its influence, making it impossible to use usual metrics to explain the spatiality of nested catchments. Similarly, water leakage from one catchment to another increases the difficulty of tracing water trajectories. Rivers cannot be understood by a panopticon view. Fragments, drops, elements: the river can only be grasped through windows of time. Observation will always be incomplete because water is what connects: it is difficult to know the sources and the routes, which makes it difficult to predict the quantity and quality of this resource. The micro (a drop) opens up onto an understanding of the macro (land uses and their disturbances), shaping a new cosmology with new metrics which would demand that we shape new cosmograms, as defined by Tresch, to understand these relationships. These links between the microcosm and the macrocosm are revealed by the tracing of biogeochemical cycles. Indeed, the scientists trace the cycles of elements such as nitrate, phosphorus, calcium, which pass and form through the CZ through observation of the river. These elements react, move, synchronise, correlate or not. Knowing their speed is more important than quantifying them to monitor the disturbances caused by the Anthropocene. Human activities are imprinted on these cycles and can easily be traced by geochemistry. These activities are literally everywhere, because they modify the smallest elements on a large scale and cause certain cycles to change or even collapse. As a consequence, tracing human signatures through chemical cycles is a new way to conceive, to understand the Anthropocene, while putting them among other chemical cycles, thus overcoming the human-centred narrative that the Anthropocene conveys and moving towards a more cosmopolitical view where it is a question of understanding the life cycles of all the entities that live in a landscape.

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6 Atmosphere

6.1 Introduction

Air pollution, heat waves, smoke from burning forests: the air we breathe is more and more threatened by the Anthropocene. Although there is no doubt that the disturbed composition of the air results from human activities, in the atmosphere chemical ingredients mix together, and it is therefore difficult to distinguish between human and natural processes. The atmosphere is commonly considered unstable, ungraspable and turbulent. Unlike the soil or the river, the atmosphere is not considered to be an easily defined entity. How do scientists in the Critical Zone get to know this elusive entity? How can they record its trace?

In this chapter, we will follow what the atmosphere is and how the scientists trace the complexity of this natural entity that is air, which is usually not visualised on geographical maps. We will see what the atmosphere is when we follow the work of the scientists. In order to be measured, atmospheric particles must be captured at some point with an instrument. By focusing on trees as sensors, scientists are not measuring the global atmosphere but the lower atmosphere, the part of the atmosphere where living beings live, i.e. up to the top of the tree canopy, so the forest becomes a network of sensors to locate the atmosphere (part 'Observing'). These trees are analysed, decomposed, to access a microscopic world from microorganism to carbon molecules which are controlling the atmosphere (part 'Decomposing'). In the part 'Tracing', thanks to these observation and decomposition procedures, scientists manage to trace and discover an unsuspected atmosphere folded into the space of the ground. In the last part 'Connecting', the scientists address the issue of the global atmospheric scale by linking the damaged locations to the sources of this damage, thus recommending different models to previous climate models to better cope with the perturbations.

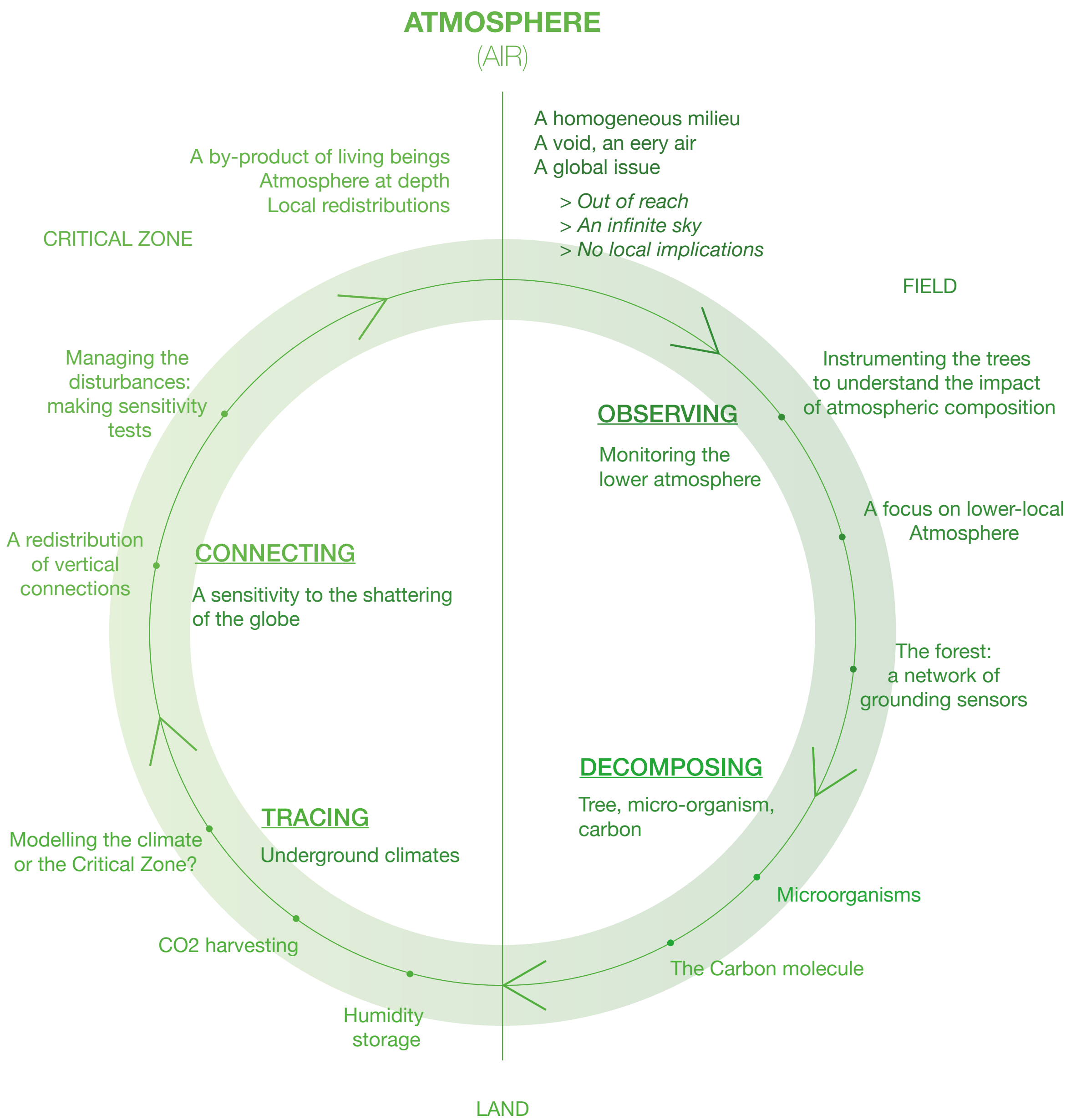

Diagram 5: Chapter ATMOSPHERE

6.2 Observing: monitoring the lower atmosphere

How do scientists overcome the obstacles to observing the atmosphere? Indeed, the atmosphere is the part of the Critical Zone that seems to be the most difficult to capture. It is through the trees that the scientists grasp the atmosphere and more importantly how it affects the entire environment. As the trees are monitored, the forest becomes a sensitive infrastructure.

The definition of the Critical Zone is that it is an area of the Earth that extends vertically from the tree canopy to the depths of the Earth. In my fieldwork, I collected a lot of evidence about this depth (see earlier chapters on soil and rivers), but little about the 'atmosphere', although it seems to be all around us. I realised that it was actually more complicated to observe and that scientists had to measure other entities to reach it. As the Strengbach CZO is a very complete observatory, I spent more time there and I was surprised how the scientists monitor the atmosphere.

> Fieldnotes from the Strengbach CZO, July 2019, Spruce trees station
> *Large horizontal metal trays perched on slender legs are set up among the trees. They are strange microstructures which remind me of experimental art installations, attached somehow by cables to the trees and the ground, their legs adjusting to an uneven topography. Two members of the team open tanks in the ground where the water is collected after falling into the trays and flowing into a tube to the storing tanks. The scientists rinse the bottles and fill them with this water. Marie-Claire explains that these big steel rays, perched on their precarious vertical legs, are in fact gutters that harvest the rainwater that has fallen on the branches and needles of the pine trees, and that the analyse of this water allows to understand the evolution of the composition of the atmosphere!* **(Fig.66)**

To understand what is being transported by the atmosphere, and whether this causes a balance or disturbance in the composition of the lower atmosphere which affects local places, scientists need to monitor the entities that receive these inputs: they instrument the trees to understand the impact of atmospheric composition. Clouds carry chemicals from the atmosphere and release them through rain. At the Strengbach CZO, this rain is

Fig.66. A gutter under a spruce tree
Some trees have died due to drought, parasites and soil acidity at the Strengbach CZO.
Photography by the author.

acid, resulting from a polluted atmosphere. Because water carries elements, the scientists collect rain drops. Therefore, gutters are installed under the trees and they collect rainwater which chemical composition charged with pollutants or nutrients is studied **(Fig.67)**. The top of the tree, the leaves of the canopy absorb all kinds of chemicals carried by the atmosphere. In the Strengbach CZO, in the Vosges forest in eastern France, the spruce station encompasses a large patch of forest. The spruces make up 80% of this forest: they are cut down and marketed **(Fig.68)**. Forest health decline has been observed over the last 4 decades due to soil acidification and nutrient leaching into the soil caused by these acid rains **(Fig.69)**. In addition, these already weakened trees are also strongly affected by storms, water stress and drought, as well as by bark beetles whose life cycle increases

Fig.67. Gutters collecting rainwater under the trees
Marie-Claire collecting water from the gutters. The gutters collect the water that has passed through the needles. The laboratory analyses the chemical composition of this water (Strengbach CZO). Photography by the author.

with climate change. There are two very different types of forest within this small watershed of 80 hectares. One is in bad health, the spruces station, and the other is in good health, the beeches station. The beech station is located on a heavily forested slope, rainfall is also collected under this species. Both stations are equipped to monitor and collect rainfall loaded with chemical elements from atmospheric dust, which passes through the canopy. Throughfall is the term for rainwater under trees: it is more loaded with elements. The rain interacts with the surfaces of the leaves or needles which are covered with dry deposits, accumulated dust, and which are washed away by the rain. Trees breathe through cells called stomata which open when water falls, and when they open, there are transfers of elements. For example, potassium is an element that is secreted in large quantities by the leaves: “if you stand under a tree in the rain, it transpires potassium”[93]. Throughfall therefore designates rain under plant cover, which is different from rain in an open field **(Fig.70&71)**.

93 Jérôme Gaillardet, 2017. 07.17

Fig.68. The Vosges forest
A central European forest in France and Germany; a continental climate with hot summers and cold winters. Photography by the author.

Fig.69. An almost dead forest
The Vosges forest. Tree species: spruce and beech. The Vosges forest was affected by acid rain in the 1980s. Photography by the author.

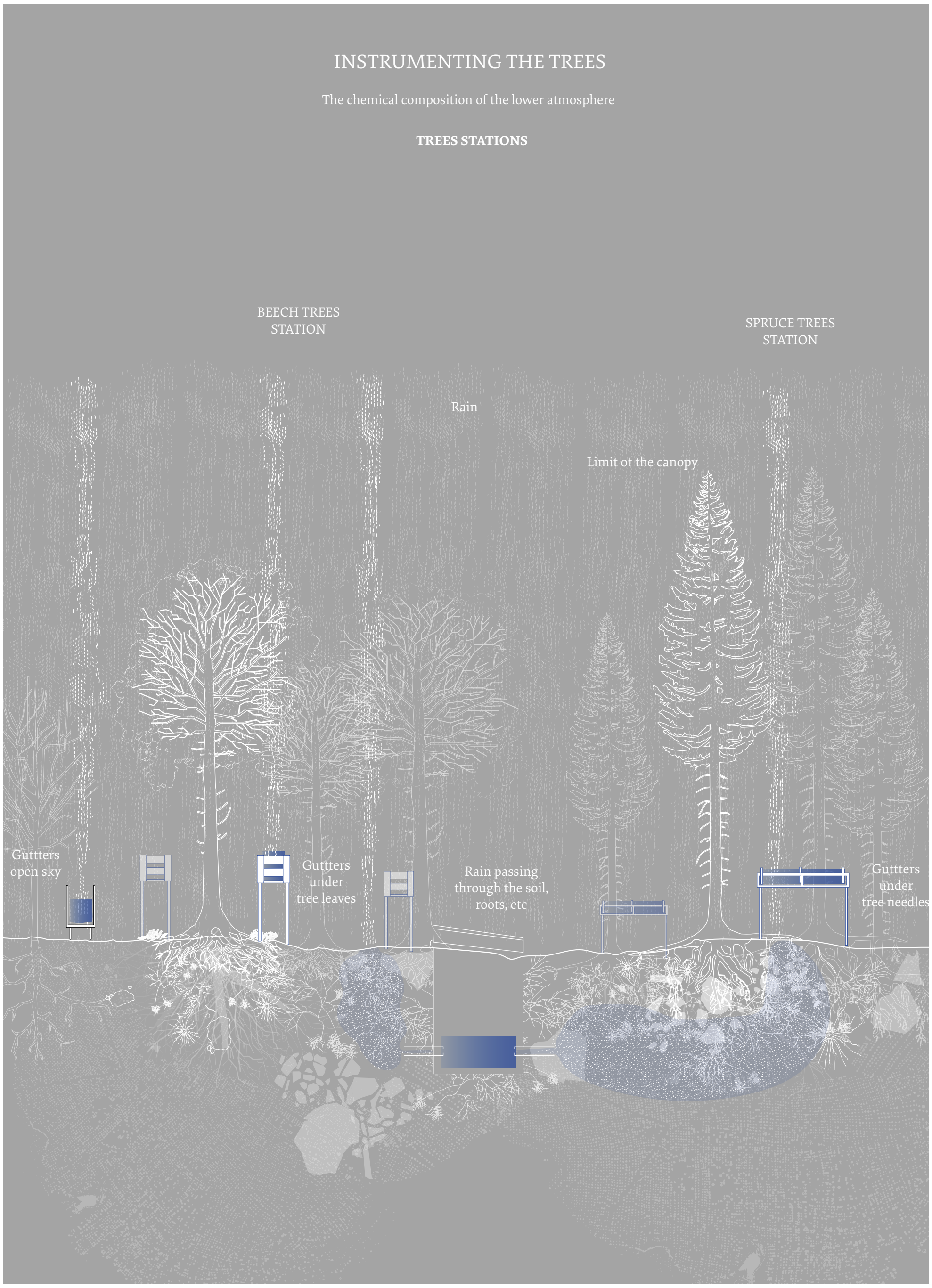

Fig.70. Cross-section of the trees station

Diagrams showing the operation of gutters at different tree stations.

Fig.71. Gutters in the snow

Although the gutters are placed among the trees, they provide an understanding of the composition of the lower atmosphere and how the trees in the forest respond to it.

These solutions are then analysed in the laboratory, which has been accumulating data for more than 30 years, showing the resilience of the Strengbach CZO to past sulphur inputs resulting from industry releasing sulfuric acid into the atmosphere. In the lab in Strasbourg, the OHGE team compares the chemical composition of the rainwater without trees contact and the water that has run off the leaves. The aim is to understand how the water is transformed on contact with the trees: do the trees effect a reduction of the acidity of the rain? By cross-checking the analysis of the chemistry of all the compartments in the Critical Zone, the scientists trace the circulation of nutrients such as calcium and magnesium, which support vegetation: how do trees, rocks, soils, bacteria, fungi, lichens, exchange their nutrients to sustain life? Do trees manage to produce more nutrients than they lose? How resilient is the forest?

At the top of the Strengbach watershed in the Vosges forest, a station is set to understand the atmosphere: the weather station **(Fig.72)**. Marie-Claire Pierret first checks the thermometer, an old-fashioned instrument, then she moves carefully to one instrument to the other, noting the measurements of the week: tubes with gradations for the amount of rain **(Fig.73)**, a strange tripod which records snow cover **(Fig.74)**, a little propeller for wind strength **(Fig.75)**. A fenced plot of land within the surrounding forest is occupied by these various instruments. Temperature and solar radiation are energy parameters. The strength and direction of the wind enable the origin of atmospheric components to be recorded. The amount of rain and snow cover make it possible to monitor variations in climatic events. However, the scientists don't observe the global atmosphere. As they explain, above 500 metres there are "well-mixed" air flows, whereas closer to the canopy there are frictional effects and turbulence. The flow tower captures this turbulence, which indicates evapotranspiration, the way in which trees moisten the air by releasing water. Evapotranspiration must be taken into account in energy calculations. The tree canopy is therefore the upper limit of the CZ: the turbulent layer is part of the CZ, but above it can be ignored because it is homogeneous, i.e., there are no variations. Scientists in the CZ measure this layer, which is the lower atmosphere, i.e., the atmosphere at a particular location. Their aim is not only to understand climatic variations but also to understand how this can affect the whole Critical Zone, all its entities. That is why they are interested in the 'lower' atmosphere, to be differentiated from the upper one which has no impact on the CZ. This lower atmosphere is delimited by the trees, that is why it is so important to monitor them and by extension the whole forest.

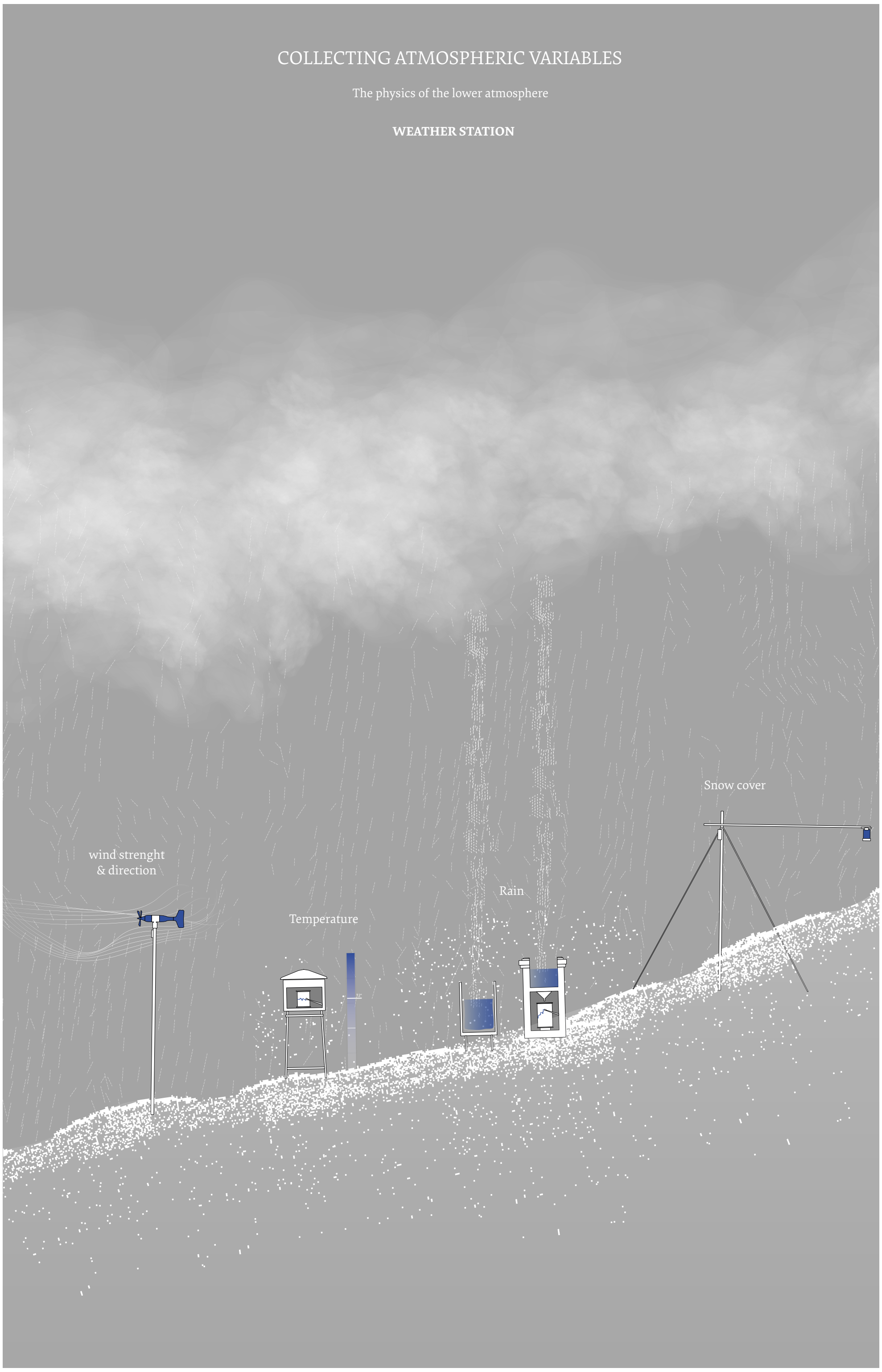

Fig.72. Cross-section of the weather station

Diagrams depicting the various instruments of the weather station. Drawing by the auhtor.

Fig.73. The weather instruments in a parcel at the top of the watershed
Temperature monitoring instruments at the weather station. Video still Sonia Levy.

Fig.74. Snow cover recording nstrument
In the parcel at the top of the watershed. Video still Sonia Levy.

Fig.75. The anemometre
Monitoring of wind strength and direction. Video still Sonia Levy.

Scientists observe atmospheric variations and especially how the forest reacts to disturbances. Through the drops that touch the leaves of trees, there is a multiplication of intermediate objects and entities to record the atmosphere: dust, tree, leaves, rain, drops, gutter, bags, samples, machine. In the field, the forest is extensively monitored **(Fig.76)**.

Fig.76. Set of forest sensors

Forest observatories are equipped with a variety of instruments, from the depths of the ground to the atmosphere. This equipment constitutes a network of ground sensors. From left to right: a water collector in the Puerto Rico CZO, a biological sensor (PR CZO), a solar radiation recorder (PR CZO), and piezometers in the Strengbach CZO. Photographies by the author.

After the weather and the tree stations, I follow the scientists through the watershed in the search for the scattered devices that collect more water, leaves, branches, at different places and different altitudes. A myriad of instruments is distributed in the watershed: tubes to collect the drops in different places, the weather station concentrating many instruments, eight piezometers, a good number of nets that collect the leaves **(Fig.77&78)**, tanks in the ground that collect the water passing through the ground **(Fig.79)**, plus the gravimeter and the riverlab we described in the previous chapters. Some instruments need power, others need roads. The infrastructure is therefore being redeveloped, not for tourism or for the timber industry, but for observation and detection **(Fig.80&81)**.

Fig.77. Nets under trees
Two nets collecting tree biomass (branches, leaves, organisms) to analyse its chemical composition, in two different forests: tropical rainforest (PR CZO) and continental forest (Strengbach CZO) undergoing severe drought (July 2019). Photographies by the author.

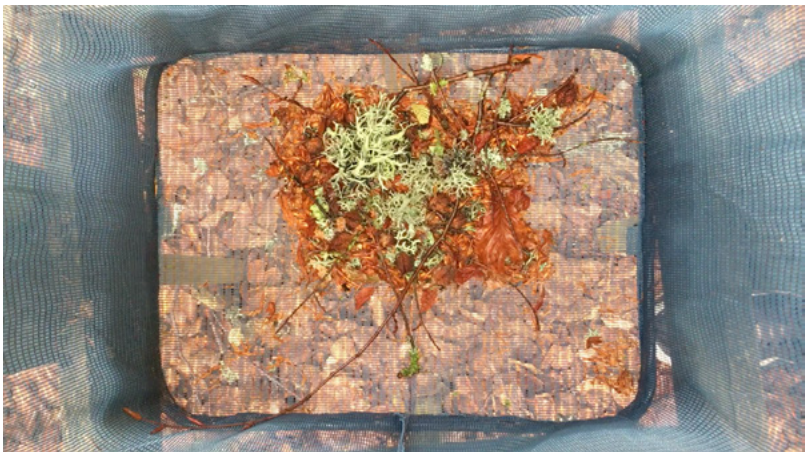

Fig.78. Organic matter
The content of the net under the beech trees at the Strengbach CZO. Photography by the author.

Fig.79. The tiny lysimetre
The ground of the forest is also monitored, lysimetres collecting soil solution to be analysed in the lab. Video still by the author.

Among these devices, the trees are the most important stations in terms of surfaces and there are the stations where the scientists spend more time. The tree and its gutter become a sensor, a third type of instrument that helps scientists understand how the chemical composition of the atmosphere 'breathed' by the trees has an impact, changing the whole ecosystem as they interact with biotic and abiotic worlds, recording atmospheric parameters. If the tree is an instrument, then the forest becomes an entire system of observation, a network of grounding sensors. The whole forest is therefore monitored. Not by a remote sensing satellite, but by a network of micro-sensing technologies that are mainly distributed among the trees. The CZO is a new landscape where the environment is no longer a backdrop for the installation of sensor devices. Indeed, distributed and articulated sensors produce discrete and localized data sets for specific purposes. Gutters, tubes and nets form a network of sensors that enable scientists to perceive complex interactions. This is the opposite of a global observation system such as climate observation. The distribution, the specific place of each instrument apparently random from an external point of view, is in fact precise and adapted to the specificities of the forest. The tree-related instruments make the processes interpretable and therefore present: the landscape is not 'out there'. This is a monitored landscape that brings complexity to its understanding.

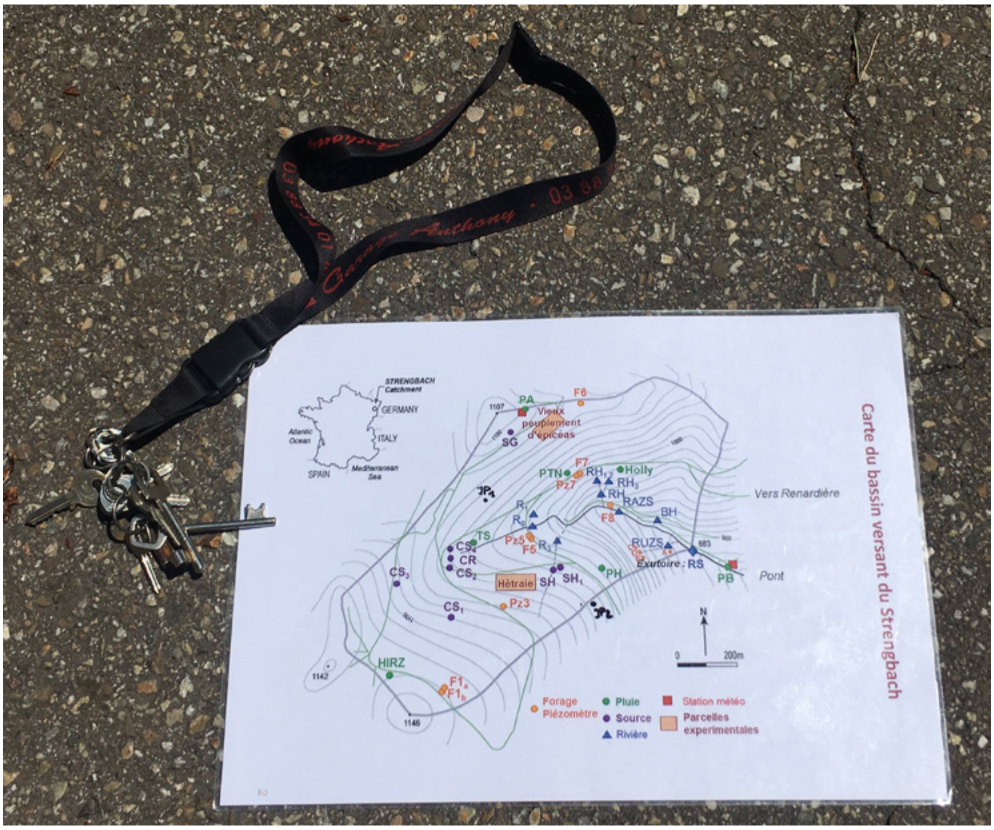

Fig.80. The map and the keys of the stations
Map of the stations at the Strengbach CZO and keys opening the parcels were the instruments are located. Photography by the author.

Scientists focus on the tree, which becomes a sentinel to trace the composition of the atmosphere. Trees collect on their leaves the daily composition of the atmosphere that scientists harvest. In combination with other instruments scattered throughout the forest, a low-tech detection infrastructure is deployed here. The instrumentation transforms the understanding of landscape, which is not a passive background, but which itself records, feels and provides the scientists with information on the variations in the atmosphere. From background, the forest provides feedback. Following the scientists, the atmosphere is decomposed to trees, but we will see in the next part that the trees in turn undergo a metamorphosis, because the scientists' aim is not only to observe the variations, but also to determine *who* makes up the atmosphere.

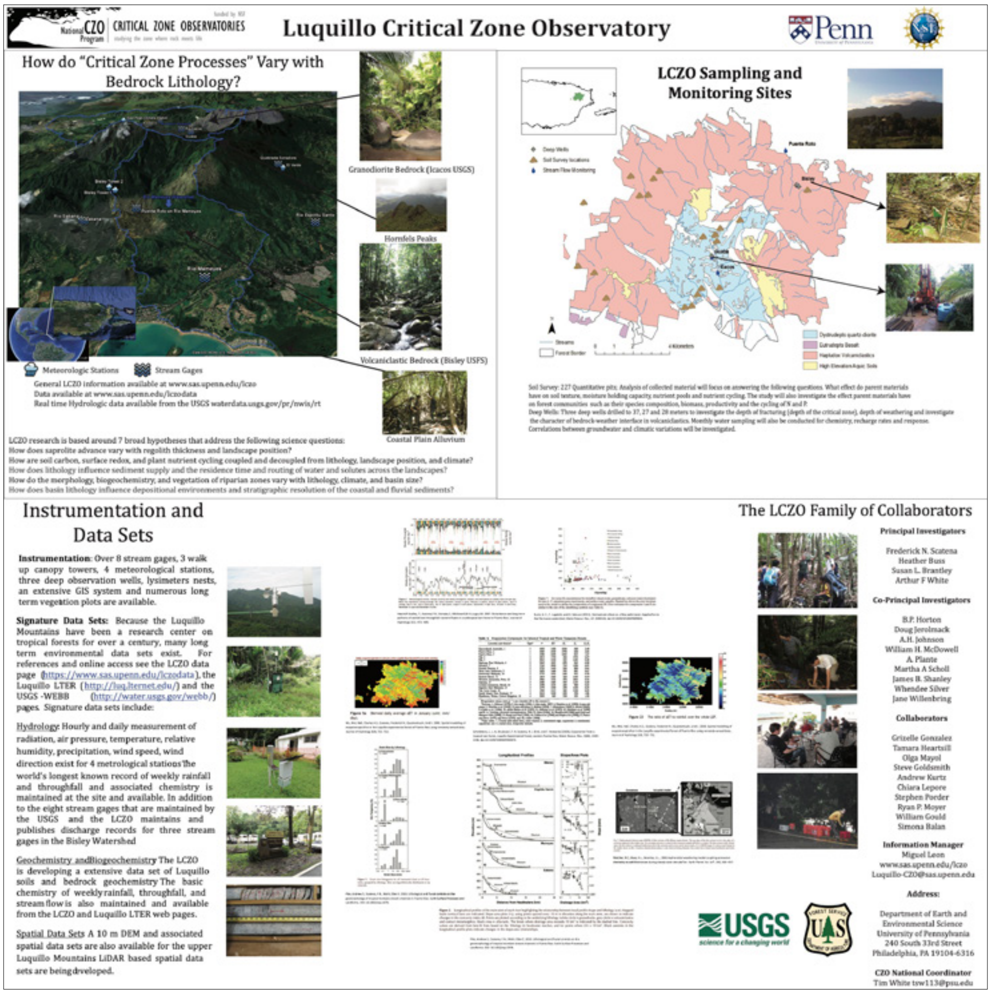

Fig.81. Example of a scientific poster

Poster of the Puerto Rico CZO showing the variety of instruments and the monitoring sites.

6.3 Decomposing: the tree, the micro-organisms and the carbon

Scientists of the Critical Zone don't observe the atmosphere 'out there' but the atmosphere in interaction with a particular ecosystem which is in part shaped by this atmosphere, such as the forest. The tree is the gathering point, the collector through which everything is exchanged and passed. It brings together micro-organisms that scientists detect by decomposing the tree. They then are able to observe the atmosphere as a product of microscopic actions such as microorganisms and molecular chemistry.

The Vosges forest, where the Strengbach CZO is located, is a contrasting environment with healthy and diseased trees. For the second time, I return to the Observatory, this time in winter. A few weeks before, there was a big storm. Many trees, especially on the tops, fell. Counter intuitively, those that remained are the dead ones. Indeed, healthy trees have branches and therefore offer too much resistance to the wind: they split and break. The view is depressing **(Fig.82)**. Only those without bark are left, eaten by parasites **(Fig.83)**. Here and there, trunks cut to two metres, sharp wood fibres waiting, wood shavings everywhere, or even large trunks once tall and proud, now lying on the ground, soon to be covered by the white mantle. The last gutters under the spruce trees were also damaged by the storm. I follow the scientists in their routine measurements. After collecting water under the dead spruce trees, the scientists continue to the gutters under the healthy beech trees **(Fig.84&85)**.

Fig.82. The forest after the storm

After the storm at the Strengbach Observatory. In March 2020, the gutters under the trees as well as the trees themselves were destroyed. Photography by the author.

Fig.83. The parasite eating the tree trunk
Another parasite is the bark beetle, an insect that lays larvae under the bark of the tree which feed on the sap of the spruce (Strengbach CZO). The tree is no longer innervated and slowly dies. The bark beetle is native to the region but its spread is accelerated by climate change (increased breeding periods). Photography by the author.

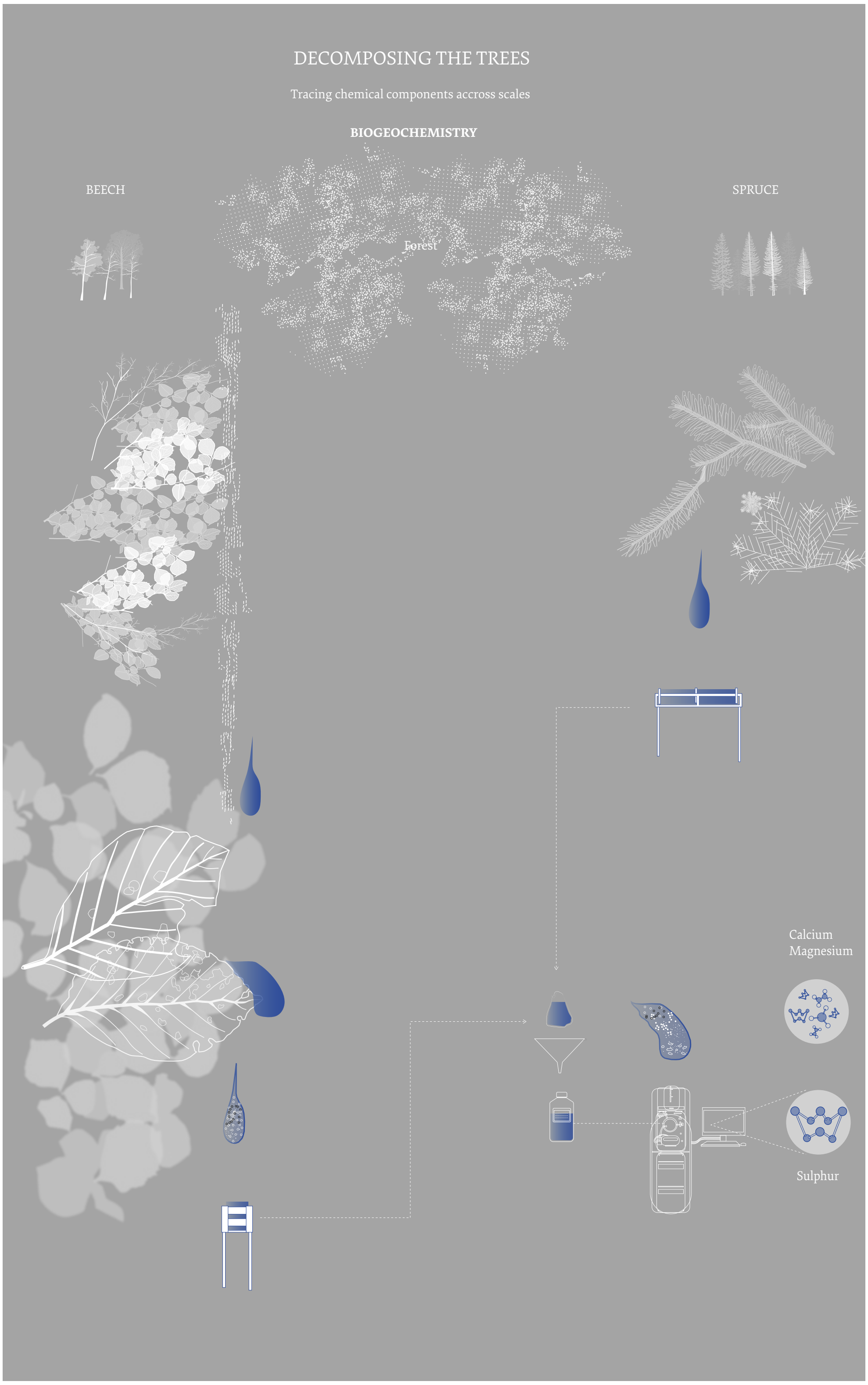

Fig.84. The process of lab decomposition

Diagrams explaining the process of collecting raindrops passing through the leaves until they are analysed in the laboratory to determine their chemical composition: the impact of sulphur (causing acid rain) or the capture of nutrients (calcium, magnesium, etc). Drawing by the author.

Fig.85: Gutter under beech trees
This is another station on another side of the mountain, covered with healthy beech trees. These trees are native to this forest, whereas the spruces have been imported for the timber industry. Photography by the author.

Fieldnotes from the Strengbach CZO, March 2020, Beech trees station

We walk down to the beech station. This part of the forest has been preserved from storms, the trees are denser and less fragile than the spruces. The contrast between the two plots is sharp. Here, the trunks of the trees are covered with a protective layer of lichen **(Fig.86)***. As we walk with Marie-Claire and Pierre, they explain to me that lichens have the property of curing tree diseases and purifying the air; they live in symbiosis with them. Moss is a sensor, or biomonitor, that scientists observe to detect changes in the environment* **(Fig.87)***. Lichens are species derived from an assemblage of algae and fungi. All trunks are green, soft, hairy. I think of Margulis explaining that algae are a mat, the mat of life around the Earth, Gaia, which we cut and remove parts of for building construction. This mat is thin and filamentous, as is the lichen on the trees.*

Fig.86. Lychen growing on the trees trunk

From the forest to the tree to understand the composition of the atmosphere, scientists focus on the molecular scale to understand the major processes (cycles). Photography by the author.

Fig.87. Moss growing on other trees trunk

Moss covering a beech tree at the Strengbach CZO. The moss is a biosensor, its presence signifying a healthy environment. It lives in symbiosis with the tree, helping it to capture CO_2. Photography by the author.

A branch of CZ scientists study the role of bacteria, they are geomicrobiologists. It is increasingly evident that bacteria contribute to the transfer of elements through the compartments of the CZ. Marie-Claire and her team at the Strasbourg laboratory dissolve plants and trees in solution, and demonstrate that there are always bacteria inside. Nutrients or pollutants such as heavy metals are transported by the bacteria too. Bacteria are also responsible for good plant growth. Nitrogen makes up 70% of the atmosphere and plants need it to grow, but they have not developed a device to fix it. Consequently, it is the bacteria present in the plants by symbiosis that fix this nitrogen. The figure of the tree as an atmospheric sentinel complexifies. The whole system is even more complex and requires new methods of observation. In her office, Marie-Claire explains that "from the aerial chlorophyll, the root supplies sugars to the fungi and in exchange, the fungi help the roots to recover nutrients such as calcium or magnesium from the soil by secreting acids. This must be taken into account, which is why the root is considered to be a box with its mushrooms. When I look at what is happening, I see it all"[94]. From the scale of the leave and drops of water, the lab work deals with the scales of roots and fungi deep below. Jenny Druhan, from the Eel River CZO in the US, a Douglas fir and mixed conifer-deciduous forest, observes similar phenomena, even if the Californian climate is very different from the Vosges one. "The absolute tip of the end of root, the deepest part of the root, the life part of the root where it's growing, secrete or exude or give away what it's called root exudate, which is just basically a huge bunch of organic carbon of different forms, and there is an entire biome of fungi or microbes that live around the roots and uses this stuff."[95] By breaking down more deeply the role of each element, the scientists reveal that the very tip of the roots, deeply embedded in the soil, is able to create a 'world' for itself. Trees connect air and soil, making liveable worlds at different scales. An important part of what sustains trees is themselves, by recycling organic matter and thus keeping our atmosphere in balance.

I follow the scientists through the dense rain forest at the Guadeloupe CZO. Our progression is hampered by emmeshed vines, creeping roots that grab

94 Marie-Claire Pierret, 2019.07.11
95 Jenny Druhan, 2019.06.01

our feet and ferns with razor-sharp foliage that cut into our legs and arms. A charming and flourishing forest! **(Fig.88&89)** But astonishingly the scientists explain that its soil resources are very low and that the forest can only rely on its recycled part to maintain itself. It is called the "floating forest" because the forest does not seem to be bound to the nutrients deep down: they can't reach them because of the thickness of the CZ, the soil litter layer, that hampers them to break deep rocks for nutrients. They thus recycle these nutrients on the surface in a continuous uninterrupted loop. It is possible because the dead trees are not removed and so decomposed, allowing the nutrients to feed young trees. On the contrary, in the Vosges forest, the trees are cut down for woods so the biomass is exported and there is no biological recycling possible. Through different CZOs, scientists follow different kinds of forests and so various atmospheric compositions: with more or less pollutants or nutrients, some actively maintained by microscopic actions, some highly disturbed by human activities. It questions the role of Life in the understanding of the Critical Zone. However, it is still poorly understood because of a lack of measurement: "we cannot measure Life, we don't have the measurement parameters, i.e. we don't know which parameters we have to measure", explains Jérôme. Scientists define Life as "small contingent bifurcations" that they observe. CZ scientists measure the effects of invisible things, such as erosion, which is an effect of living organisms, but they cannot say to what extent it plays a role, let alone explain it: "Life is everywhere, but I can't explain it", Jérôme concludes. However, scientists do not spot life as a form, but by tracing chemical elements, they spot it as a signature, as we saw in the previous chapter on river. Indeed, what is the atmosphere, if not a living by-product, that is the unintended result of a living being, such as tree, human or microorganism?

Fig.88. The forest in Guadeloupe...

The forest of Guadeloupe in the West Indies. A tropical forest, with a tropical climate (heavy rain and heat), on a volcanic island in the Caribbean Sea. Photography by the author.

Fig.89...also called ‘the floating forest’

The Guadeloupean forest. Multi-species and stratified forest. This forest is known as the ‘floating forest’ because the bed rocks are very far from the surface. Photography by the author.

“There is water, oxygen and CO_2 in trees, but if we want to observe this, the tree is not the right representation, we have to study the molecules of the tree.”[96] About two billion years ago, cyanobacteria began to produce oxygen as a waste product of their metabolism, killing all anaerobic organisms (those for which oxygen was toxic), while providing a myriad of other organisms with new opportunities to grow and flourish. This includes humans whose residual metabolic product - body and extended body (technology, industry), is carbon dioxide gas. Today, this by-product threatens to kill aerobic organisms because this CO_2 waste fills the atmosphere, causing a chemical imbalance. Understanding the carbon molecule is to understand the relationship between the atmosphere and the living world. In the CZ literature, chemical formulas fill papers. These formulas are the results of the lab work. At the IPGP, the scientists work in the white rooms to isolate the elements and measure each of them with the spectrometer machine. Posters, Mendeleiev table and other items cover the wall: here we deal with the chemistry of the Earth. As an architect, I am not familiar with the principles of chemistry. But to understand how the elements are decomposed, we need to study some chemical details which I have been informed through the interviews I conducted at the IPGP. There are several versions of the same element called isotopes. ‘Isotope’ in Greek means the same place because isotopes occupy the same place in the table of elements. However, the mass of their atomic nuclei differs. Isotopes have the same physic-chemical characteristics, except for small differences. These small differences mean that there are fractionations, i.e., when transferring from one compartment of the CZ to another. During this passage, there may be a small preference for one of the two isotopes. Therefore, these isotope fractionations can be used to trace certain processes. For example, carbon, C, one of the fundamental basic elements for organic, living matter, has 3 isotopes: 12, 13 and 14, which are used to trace different processes. C14 is unstable, reactive, it decreases, and so it is used as a geological chronometer to trace processes over long timescales. C12 is life and it is the trace left by the plant. This Carbon moves in and out of entities, but as soon as it enters diffe-

96 Jérôme Gaillardet, 2019.01.17

rent entities, it is no longer CO_2 carbon. It becomes plant organic matter carbon, then it becomes animal organic matter carbon, then it is humus organic matter carbon in the soil where it can reside for 5,000 years, then it is eaten and comes out as CO_2 carbon. It is therefore carbon, the atom in the Greek sense (small indivisible particle) because it remains carbon but in fact it changes shape all the time. Geochemistry retraces the role of the element through its metamorphosis in the CZ which can be known during the decomposition of matter on a molecular scale. A cycle is a succession of reactions. A reaction is the moment when the molecule breaks and combines to form something else. But scientists don't look at the forms: "the principle of a cycle is that forms can change, carbon is alternately CO_2, CH_3-, etc", explains Jérôme. A cycle is the study of the sequence of these reactions, which can also be understood as trajectories through the CZ. These reactions occur when there is an encounter, a contact, a bifurcation with another element in a change of environment. This can be compared to a ballet of elements: they come in, go out, disappear, come back differently, change, play other roles, and so on. In cycles, forms are not stable. For example, carbon is constantly changing its composition. Each element reacts according to a set of preferences that the geochemists study. The carbon molecule changes shape, state, according to its associations. The Carbon cycle has at least three cycles. The most obvious is the trees which use the carbon dioxide on a scale of 100 - 200 years and then release it back into the atmosphere. If this flux, which is enormous, is cut off, it will take 10 years for it to disappear from the atmosphere. The scientists consider it as a bathtub with little water, but huge inlet and outlet taps. This means that the CO_2 in the vegetation doesn't stay there for long. Then there is a second cycle, which takes a little longer: the carbon dioxide from the air that reacts with rocks where it is transformed into a bicarbonate anion that goes into the ocean and precipitates as limestone in corals, by plankton etc. There, it is stored for 200 million years, but it is very small stock: about 100 times less than the carbon released into the atmosphere. Finally, the third cycle is the degassing underground in the mantle, where the mantle melts. The CO_2 concentrates when it melts for billions of years. It is these last two cycles that have purified the earth's atmosphere, that made it habitable. However, it is with the first one we have to negotiate, the scientists warn. That is, the one that involves trees. The disturbance could be understood as a problem of distribution of an element whose normal and balanced distribution across the Critical Zone to allow life is disrupted. CO_2 gas is a climatic agent, and it is in our interest that the exchanges between it and the limestone remain fluid, which is no longer the case. Another important element is carbon in the form of organic matter, i.e., fossils, ancient living beings that have been sequestered for a long time in the depths of the Earth. As Jérôme explains, human activities bring them "back here", as if "we brought them back to life" or rather, as if "we breathed them in far too quickly". The Anthropocene is the disruption of a cycle by human activities, in this case the acceleration of the average respiration of CO_2.

To understand the atmosphere, the scientists need the trees, but if we had to describe these trees, it will not be with a trunk, branches, and leaves only, instead it will be through their bacteria, roots, fungi, CO_2, water, gutters. The microorganisms and the CO_2 molecules are only some threads of a bigger picture, with more threads, that is more elements and entities that the scientists cannot fully list yet. The representation of a tree as a dot in conventional mappings is simplified and does not describe its role in the making of the atmosphere.

6.4 Tracing: underground climates

By decomposing the elements that make up the forest, scientists are able to trace the elements responsible for the composition of the atmosphere, not only in the air but everywhere CO_2, oxygen and other light chemical components are found. Where is this research taking scientists? What new understanding of the atmosphere does it bring? By tracing the atmosphere, scientists are discovering another location for it.

During the visit of the Puerto Rico CZO, located in the wet and hot rainforest composed of palms trees and other exotic species, Jane, an American scientist, shares extraordinary stories with me about trees there and their resilience to hurricanes. The Puerto Rico Forest is similar to the one in Guadeloupe, the neighbouring island of the Caribbean Ocean: it draws its nutrients from the atmosphere by the winds carrying Sahara sand and dust containing calcium, magnesium, etc. Some sides of the mountains undergone severe storms, and so some of the trees have adapted to those conditions. Palm trees develop a strategy to keep the nutrients during heavy rains and storms. They act as umbrellas: only half of the rain falls on the ground because the leaves protect them and prevent the nutrients (their food) from dissolving away from the roots. Trees also slow down erosion, which is why it is so strange that a tropical climate does not have so much erosion: “trees shape their own landscape, they play a very important role”, Jane says **(Fig.90)**.

Fig.90. The palm tree under the rain

Palms have developed strategies to optimise rainwater collection, with drops running down the trunk directly to the base of the tree. Video still by the author

At the Eel CZO in the United States, the scientists made an important discovery by tracing the trees. This forest is a temperate forest in California, but even so, the trees are very active agents influencing climate variations. Indeed, atmospheric climate parameters such as humidity and temperature self-regulation seem to be controlled by... roots deep down!

> “Imagine you’re here, it’s really dry down to about 16 meters, so we’re at the end of the dry season, the roots are going down about that far, so they’re dry, everybody really need water, and it starts to rain. And the first thing that you should see it’s that the upper layers start to saturate but nothing gets further down, and so as they started to reach their storage potential, the water is allowed to move further and further down into the Critical Zone. If the trees weren’t there, it would go straight down to the bottom to the water table, but the trees are causing that delay or that slowed time over which the water can move down, and so this is the storage of rock moisture. Then we go back into the dry season and the trees are like on a diet, they [are] sort of rationing their water and slowly sipping away on that until eventually using it all, and then you go back into the rain season again.”[97]

The roots of the trees therefore direct the water downwards until it reaches the rocks and then stop this infiltration so that they can keep it, store it for the dry season: “the trees are pushing that water into the rocks and basically storing it, it’s like a bank account. And then during the dry season they sip on that water”[98] with their roots. The aquifer, for its part, is left out of the process, it “has no idea that is raining.” It is only when the tree water reservoir is full that the water table can be recharged. Humans are competing for this resource as we draw our water from the water table. But if the trees “don’t put that water back into the rock, above the water table, they are in trouble when the next drought will come.” Jenny explains that the Californian forest fires that have been burning so much in recent years may be due to the depletion of their water reserves and that this in turn may be due to the increased proportion of the water supply diverted for human use. Scientists grant trees, or their roots, the power to divert water, and thus gain specific agency **(Fig. 91)**. This power is understood as a plasticity, a way of understanding their world and acting accordingly.

97 Jenny Druhan, 2019.06.01
98 Idem

Fig.91. An uprooted tree in the Vosges

The scientists discover a fallen tree at the Strengbach CZO which allows them to observe the rock plate under the soil complex (still attached to the tree's roots, vertically in the picture). Water flows over the rock, previously controlled by the trees that fractured the rock to draw water from it, and eventually causes the tree to fall. Photography by the author.

Sylvain Kuppel is a hydrologist working on a model to understand the CZ and especially the relationships between water and plants. During the interview I conducted with him, he told me how much this work has changed his conception of the world: "What I gradually became aware of is that the uptake of water by plants can affect the water that flows afterwards. This power of access to water by plants. The ability of plants to go in search of water and their plasticity."[99] Plasticity is the ability of plants to transform and reconfigure themselves, particularly through their roots **(Fig. 92)**. Plasticity can also refer to the adaptability made possible by the faculties of receptivity to the surrounding world. "The roots are making a more favourable environment for itself", told me Jenny. The parallels with Gaia Hypothesis are quite obvious: "these roots seem [to be] driving a lot of the story. The roots themselves are responding to conditions on the surface like day time, night time, and rainy season, dry season, temperature. So understanding that surface - subsurface link has become very important."[100] Not only do the trees act for themselves, are the central protagonists of the story **(Fig.93)**, but it is as if there is also a deep climate, a deep atmosphere where water, oxygen and roots come together, like an inversion of what is happening on the surface. It's an inversion of our understanding of what we think that the climate is only a 'surface' issue. Scientists explain that important reactions actually take place deep down, as if the depths reflected the surface in climate variations, as if there was an unexplored atmosphere at depth.

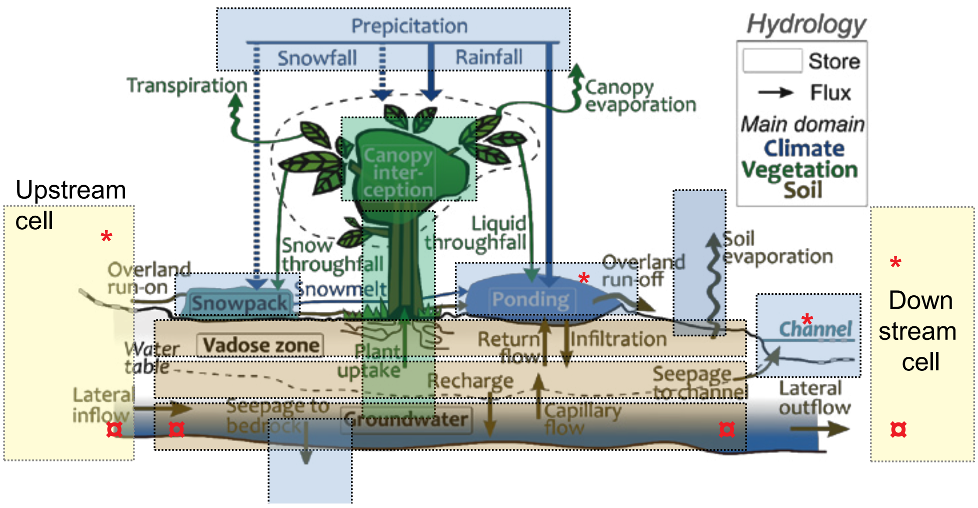

Fig.92. A model for the Critical Zone
During our interview, Sylvain Kuppel shows me a diagram explaining the parameters of the model he is developing. It is a complex set of vertical and horizontal interactions in which the tree plays a central role. This complexity is not taken into account in climate models, unlike the CZ where scientists multiply the processes to be taken into account. Drawing by Sylvain Kuppel.

99 Sylvain Kuppel, 2020.04.08
100 Jenny Druhan, 2019.06.01

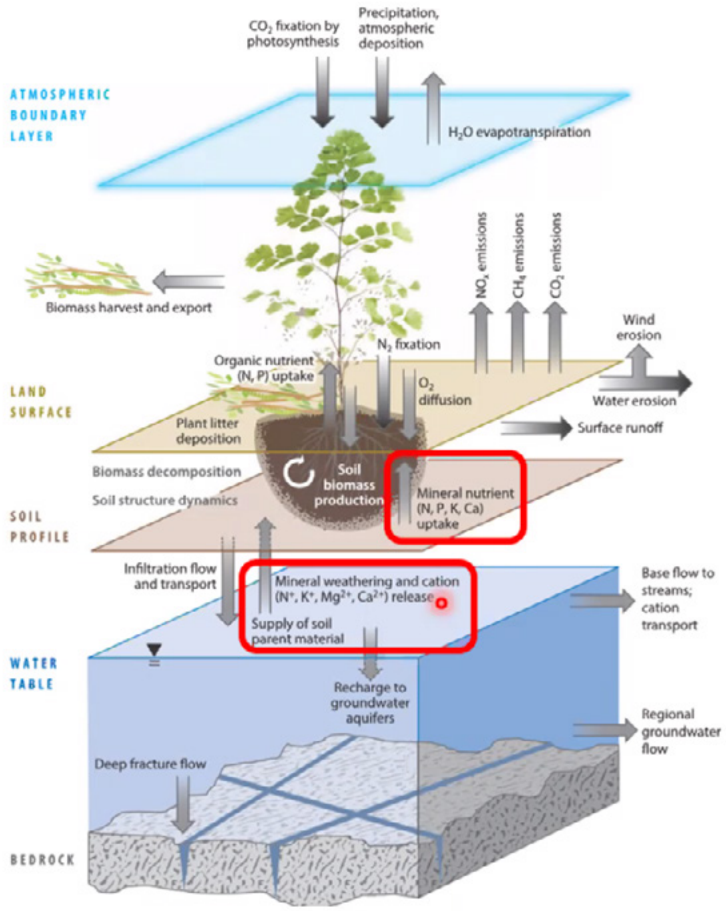

Fig.93. The CZ through the tree analyse
Diagram of the Critical Zone where the tree is a central element to understand the different exchanges between the parts of the CZ, especially to understand biogeochemistry. Drawing in Banwart et al., *Annu. Rev. Earth Planet. Sci*., 47, 59 (2019)

By tracing the composition of the atmosphere through trees, scientists continue to make unexpected discoveries. Scientists trace carbon and discover an invisible source of CO_2 that could change the rules of climate models. In the classic carbon cycle, surface vegetation made of carbon decomposes and these leaves, roots and litter become organic carbon in the soil. Microbes and fungi convert this carbon back into CO_2, which is returned to the atmosphere. This balance of photosynthesis going into and out of the soil is the terrestrial carbon cycle. The classic model indicates that all CO_2 is produced in the soil: when water falls, it transports CO_2 through this area, dissolving some of it. This CO_2 reacts like soda or carbonated water, because it becomes acidic and can dissolve rocks as it sinks. As a result, the reaction occurs in the soil and the water then descends and uses it on the rock. From this point of view, CO_2 is only produced within a few centimetres of the surface. However, recent discoveries by CZ scientists show that CO_2 could be produced deeper. Following what Jenny told me about water in the previous part, I learned how the depths keep some other secrets “there is a huge amount of CO_2 [that] has been generated meters below soil, which is crazy! Because where is it coming from?!” Jenny exclaims. Initially, her team suggests that fossilised shellfish could be the source of this CO_2 abundance, but if this were the case, the carbon dating technique would show an old carbon, which is not the case: the carbon at depth is completely recent. What causes this unexpected amount of CO_2 at a depth of twenty metres? By observing the roots, the team finds an explanation which could change our understanding of the composition of our atmosphere. Scientists discover that trees pump carbon from deep underground and produce CO_2, which contributes to the weathering of the surrounding rocks and facilitates the growth of their roots **(Fig. 94)**.

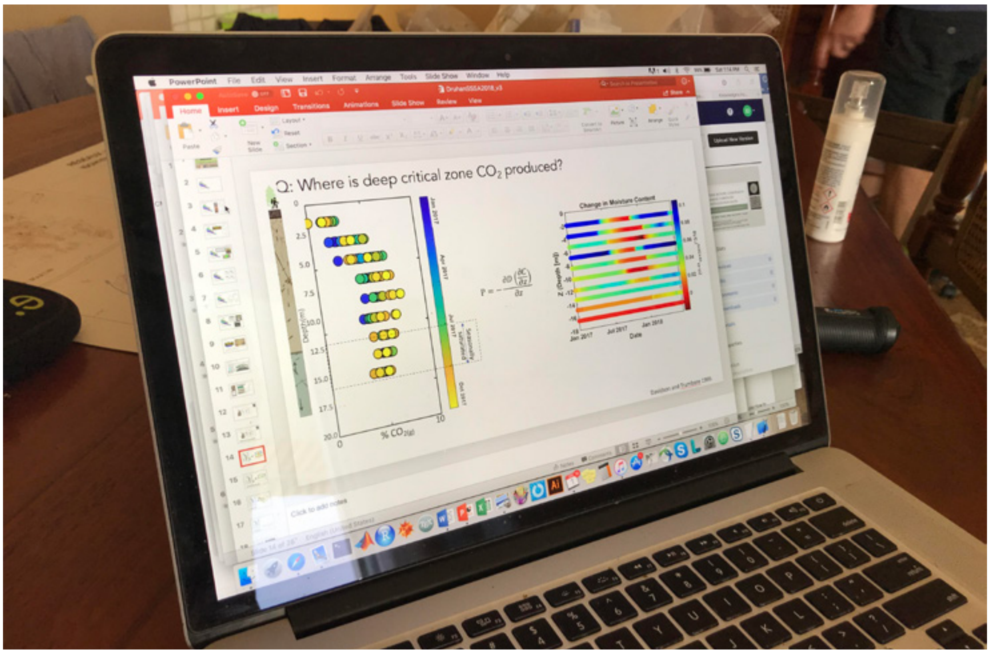

Fig.94. Jenny’s screen on deep CO_2.
During the interview, Jenny Druham shows me the graphs from her research on roots and CO_2. Her research reveals that CO_2 could be produced at unexpected depths in the Critical Zone. Photograph by the author.

The tree is not a passive element in a landscape, but a very active agent, which causes unexpected phenomena. The roots profoundly change our understanding of the places where CO_2 is produced. There is an underground climate which reflects, exchanges with and mutually influences the climate on the surface. CO_2 variations are related to the depths as the atmosphere sinks deeper into the rocks than the scientists thought. The atmosphere is all around us, but mostly inside: in trees, in the pores of the soil, in the water and in the lungs of living beings. This could pose serious difficulties for climate models aimed at predicting the evolution of CO_2. Indeed, as much more CO_2 could be stored under the world's forests, if these forests were to disappear, because of deforestation, or fires, acid rain, etc., then much more CO_2 would be released into the atmosphere. This is one of the reasons why scientists are cautious when it comes to developing models. Observing and monitoring the atmosphere traditionally means having a weather station at a fixed point that records variations. As we have seen previously, this is not the case in a CZO: a wide range of instruments scattered throughout the observatory is needed, and the main instrument for monitoring the composition of atmospheric changes is the tree. Following the CZ scientists' activities, this is not the same atmosphere as the one studied by climate modelling or meteorology. However, climate models allow to become sensitive, conscious of the variations in the atmosphere, and the CZ scientists also need them. Earth system science (ESS) then creates models that predict trends under different scenarios. However, this type of climate modelling does not give credit to CZ's results and, worse still, neglects some major problems concerning the atmosphere and its relationship with land and water. Because of the attention to the soil and all the entities that are observed in a CZO, the CZ models cannot simplify their parameters. Sylvain Kuppel is appointed to design CZ models with data from four different observatories which represent a climatic and environmental gradient: one in the mountainous Vosges forest (the Strengbach CZO), one in a temperate oceanic climate in Brittany (France), one in a dry deciduous forest with monsoons in India, and one in desertic area in Western Africa. However, climatic models from ESS don't take sufficiently into account the local conditions, their mesh is too 'large'. Sylvain is not using these models but develops a new one. Sylvain shares his screen via the Zoom meeting window. He shows me coding lines and then their visualisation: the surface of the observatory is decomposed into more than a thousand tiny pixels, all of them having its own parameters (water circulation, soil moisture, biomass characteristics, etc). Small meshes represent the entire surface of the watershed (Fig. 95). The modeller manipulates the terrain with progressive refinement; cutting, grouping, cross-checking to distinguish the soil characteristics and then grouping them together. Sylvain's models describe much more relationships than the climate models.

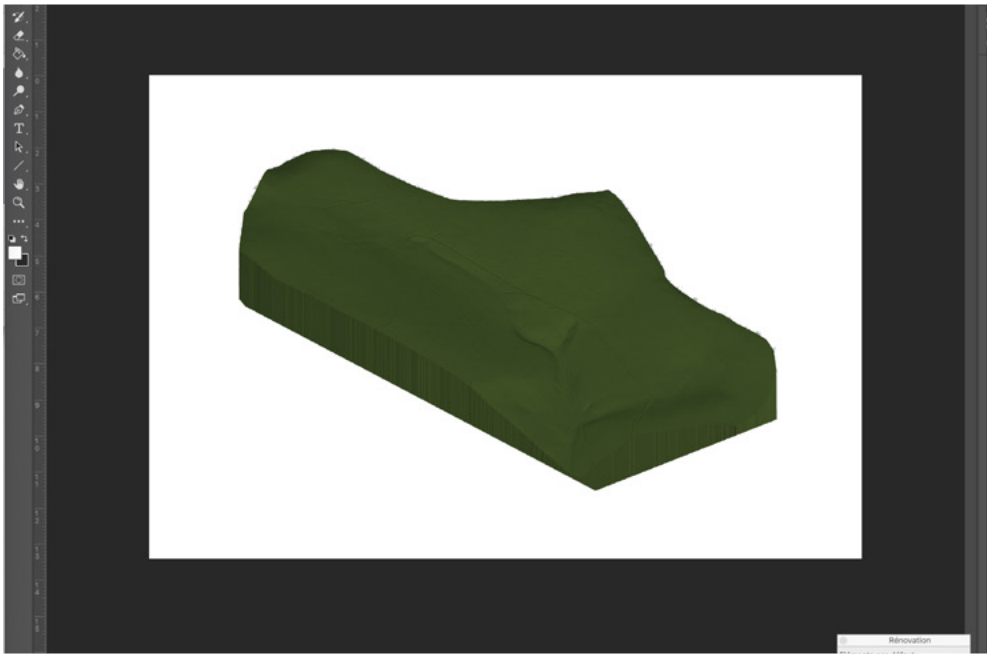

Fig.95. Meshed model of the Strengbach CZO
Model by the OHGE, uploaded on Photoshop

In the CZ model, there are more entities (the trees, the roots, the chemical element, the rocks directing the flow of water), there are more timescales to take into account and the spatial configuration is different: both deeper and laterally extended. CZ models view the atmosphere as a matter infiltrated in water and soil alike, not only in the air: "there is the upper, the lower atmosphere but also in the pores of the soil, the plants, etc"[101]. This view changes the way models are developed, with a strong relationship with the ground of the CZO. In a break during the fieldwork at the Guadeloupe CZO, I question Jenny and Jérôme about models. Jenny cautions against climate models that are used to make future predictions if the amount of CO_2 emissions does not slow down, and which are based on soil conditions such as temperature and humidity,

101 Jérôme Gaillardet, 2019.09.18

which are themselves extremely heterogeneous. Indeed, the soil composition is not exactly as the scientists previously thought, particularly with regard to the amount of CO_2 at depth, which could be much higher than that included in the climatic models. As a result, the global climate model would be made with insufficient parameters, which is dramatic because there could be more CO_2 in the soils, and therefore if forests and their soils disappear, more CO_2 would be released into the atmosphere, which would increase potential damage.

By tracing the elements responsible for the atmosphere, climate and composition, scientists are changing the traditional conception of the atmosphere as being above the surface of the Earth. The roots collect CO_2 and thus control the amount of CO_2 on an earth-wide scale. They also control water infiltration and thus evapotranspiration, which regulates the climate. There is a deep atmosphere both above and below the Earth's surface. Not only does this atmosphere extend deeper into the ground than expected, but its composition is also much more complex, a characteristic which is taken into consideration in the new models that the CZ scientists are building, encompassing more entities than those of the traditional climatic models.

6.5 Connecting: a sensitivity to the shattering of the globe

The atmosphere appears as a product of the living beings through the practices of scientists who observe, decompose and trace each element that composes and controls it. Human activities are also involved. Scientists record how industrial activities redistribute the composition of the atmosphere on an Earth-wide scale. In this last part, we follow the scientists who establish links between the Vosges forest, which suffers from sulphur emissions, and the sources of these emissions. Then, we describe how models of the Critical Zone are designed.

In the 1980s, foresters were faced with the decline of Europe's central forests, whose trees were succumbing to acid rain. This environmental crisis was raised by the media. Scientists quickly got together and expressed their concerns to governments. Acid rain was one of the first environmental damages to be addressed by strong public policies, forcing global industrial groups to reduce sulphur emissions into the atmosphere. The Critical Zone Observatory at the Strengbach catchment was specifically created to monitor the reduction of acid rain on forests. Sulphur comes from clouds, from the atmosphere, from pollution. It comes from the burning of charcoal. In the field, under the spruces where the gutters are installed, Marie-Claire Pierret explains this process: "when sulphur oxides are emitted into the atmosphere, there are different chemical reaction pathways: they can pass into the solid phase but also into aerosols. And once they are in aerosol form, in anticyclonic conditions they can be transported to another continent within a few days. This has been tracked by satellite. Acid rain is found in the glaciers of Greenland, in Antarctica, it's found everywhere."[102] It appears impossible to isolate a part of the Earth without taking into account the flows and movements that impact on the whole Earth (and continually shape it, sometimes invisibly). The local is never local - it always contains global movements, flows to some extent. The effects of sulphur are complex. Scientists explain that the problem as such is not the sulphur molecule but the way it combines with other protons which causes disturbances when water loaded with these molecules touches and infiltrates the soil **(Fig. 96)**. "Sulphur is the smoking gun of

102 Marie-Claire Pierre, Fieldnote Strengbach CZO, July 2019

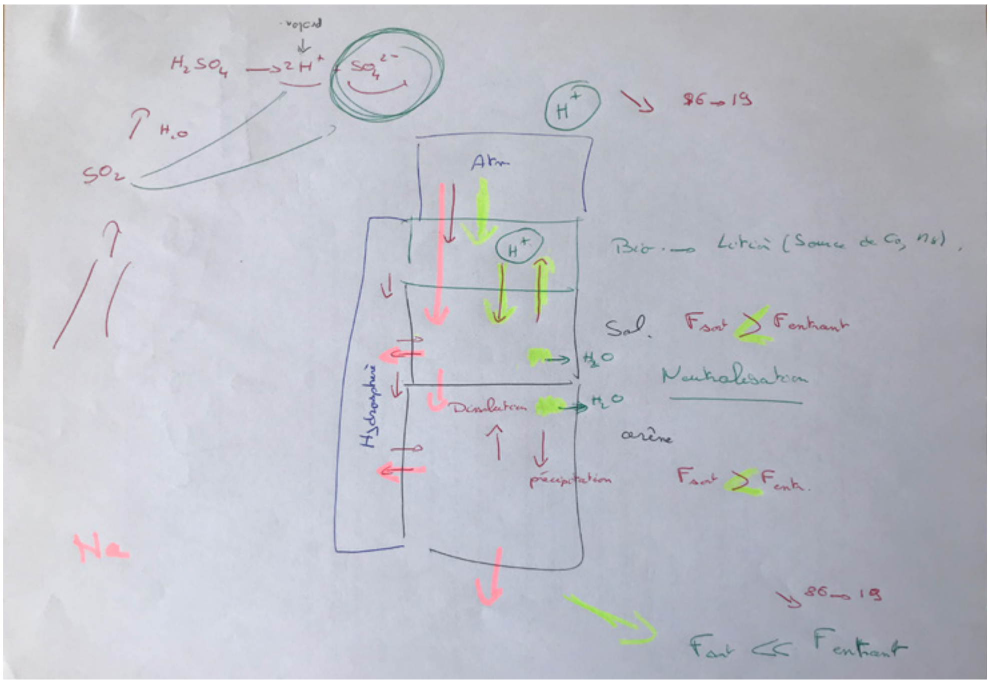

Fig.96. Scheme of Sulphur exchanges

During the interview, Marie-Claire Pierret draws the complex chemical reactions of sulphur as it passes through the different layers of the Critical Zone.

chemical transformations that occur due to protons in the soil. The Vosges forest was an area traditionally rich in calcium, potassium, nutrients for vegetation, and if you lower the pH (potential Hydrogen, because of acidity of the Sulphur), you make exchanges and you make them all go away. You wash the cation load."[103] Therefore, Sulphur triggers undesirable reactions in the soil, depriving it of the minerals that the vegetation needs to grow. Since the 1980s, the amount of sulphur falling on the Vosges has decreased from 3 tonnes to 300 kilograms **(Fig. 97)**. However, it has not returned to pre-industrial acidity. There are several reasons for this. First of all, there is a delay, a lapse of time, for the soil to recover, even if the acid rain stops, the soil still maintains its acidity. Secondly, because spruce plantations are acid trees (the acid needles cover the soil) by themselves. Instead of planting other species (beech could neutralise this acidity), industrial forestry continues to plant this species to exploit its wood, which increases the unsustainability of the forest. Since 2000, scientists have noted an increase in sulphur in rainfall, which they are able to correlate with the boom in Asian

103 Jérôme Gaillardet, Fieldnote Strengbach CZO, July 2019

industrial activities. On their graphs, they show the impact of Asian activities between 2000 and 2009. They demonstrate this correlation by measuring meteorological variations during concentration peaks and they discover that sulphur emissions can move in less than 20 days from Asia if wind conditions are favourable. Not only is a CZO a sentinel of the globalized environment that keeps historical track of variations and pollutants, but it is also a real-time sentinel that traces the most fleeting effect of pollution. Through the movement of sulphur, scientists trace the connectivity between places and activities, their overlapping, conflicting effects and the difficulty of managing the politics of these remote yet interdependent places through atmospheric dust flows. It is all the more difficult because scientists cannot always distinguish where sulphur comes from. Indeed, Jérôme explains that even if meteorological conditions make it possible to deduce the sources, from a chemical point of view, sulphur coming from the former coal basin of Northern Europe or that of recent Chinese industries is the same, it comes from the deep rocks that have been brought to the surface. The capture of sulphur by the Observatory is the crucial moment when a segment of connectivity is highlighted. Connectivity can be traced from a local point, from a component captured in one place, and then extended to the source. Then, this moment of local and punctual capture fades away again when the sulphur leaves the observatory through the rivers that carry it to the Rhine, then to the North Sea and the ocean. The sulphur remains in the ocean for millions of years and sediments in the rocks in the form of pyrite or gypsum. This is another kind of connectivity, as the element leaves the watershed and connects in a different way to another global compartment that is the ocean. Between the upper atmosphere, where they come from, and the ocean, where they leave, which can be considered the two boundary conditions, the elements are dispersed or concentrated, and in doing so, they shape local landscapes. On the one hand, anthropogenic Sulphur emissions from Asia, which are the origin of acid rain, are transported to the site in twenty days under certain climatic conditions; on the other hand, thanks to other 'good' wind conditions, the nutrients that feed the Vosges forest are brought in with the sand from the great deserts such as the Sahara. The Vosges forest lacks calcium and magnesium because of the rock's constitution. Scientists are therefore trying to understand where plants get their nutrients, where these minerals come from and how they get here. They are discovering two types of atmospheric deposits, or dust: some are natural, the sand coming from the continental crust and from the desert and spreading by aerosol, to reach even lands on the other side of the ocean like in Guadeloupe, which thus feeds on the Sahara. Other dusts are purely artificial. Some nutrients come from transcontinental anthropogenic emissions: cement factories. Some laws that have limited emissions from cement factories have reduced the sources of magnesium and calcium for the Vosges forest. Chemical flows redistribute territories, notably by crossing sovereign borders. The globe as an undifferentiated unit is not the good frame. Scientists refer to concrete and connected places: desert sands, cement works, factories, even if they are distant from each other. Atmosphere circulates everywhere, but it is also confined in space. The atmosphere of the Critical Zone does not escape beyond the borders of the earth: it is confined in them. Scientists capture feedback of the atmosphere from one observatory to another. This redefines what the atmosphere in the CZ is: something inside bodies, that is consistent, made up of elements that CZ scientists trace. More precisely, the question they ask is not what the atmosphere is, but rather what it is made of.

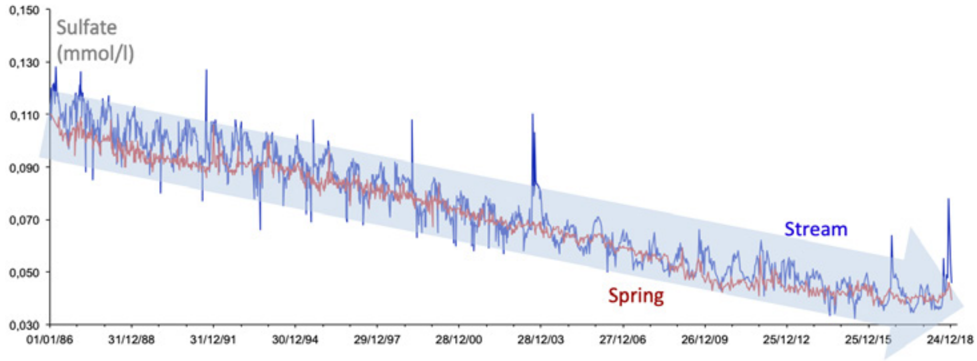

Fig.97. The sulphur graph
Graph showing the decrease in sulphur content in water at the Strengbach CZO since 1986.

All the observations, instruments, procedures of decomposition, tracing of elements of the scientists' practices tend towards the fabrication of robust models to understand Earth reactions that are poorly known in the Critical Zone. As we saw in the previous part, a CZ model is more complex than a climate model. It implies a different epistemology. Jérôme Gaillardet defines a model as something with "predictive capability". Scientists make a prediction and check whether it is correct. Sylvain Kuppel and Nolween Lesparre, modellers of the CZ, insist that it is not their purpose to say "this is how it works" to other scientists: instead they stress that the model needs to be tested. They use trial and error, start again, imagine something else. Indeed, some types of data allow the modellers to build the model, to give it "constraints", to "force" it, while other types of data are used to evaluate the model by comparing this set with the one the model generates. If the model and data do not match, the modeller modifies the parameters until they coincide with the field data. Confidence in a model is gained by evaluating it against what can already be observed. The model is therefore both constrained and flexible. The model scenario adjusts to the terrain, reacts to and updates with it, and also generates versions of it. The modeler follows the variations continuously because this allows to feed the model. There is also a movement from the model to the field to suggest new spaces, processes, elements of the CZ to be measured. As Sylvain K. explains, an efficient model triggers new measurement in the field:

> "What is interesting in a model, once you have confidence, is to explore the output or internal states of the CZ that you cannot observe and thus suggest where things could be measured, or where things could be measured at a higher frequency. In the model-to-data direction, what I find interesting is to suggest potential leads for future measurement campaigns."[104]

A model makes it possible to extrapolate knowledge to places that we cannot observe directly, or over inaccessible periods of time. Extrapolation is defined as the practice of inferring, from observable processes or behaviours,

104 Sylvain Kuppel, 2020.04.08

processes or states that escape human experience, to fill in the gaps in experience. Models integrate all the data collected on the same observatory, on soil, water, atmosphere and biomass. However, they are not “real”, the modellers keep warning me about it : “fundamentally, the model is only an approximation of reality, they simulate the functioning of a landscape on the basis of couplings between more or less known processes”[105], for example, the coupling between the energy balance at the top of the canopy and the surface balance, in order to understand evapotranspiration exchanges, coupled with equations describing the movement of water in the soil. Models are thus extrapolation, approximation and simulation of Critical Zone processes. This practice of CZ modelling engages a new relationship between the field and the lab. In the previous chapters, we have traced the back-and-forth movements of the scientists between the lab and the field, and the transportation of the lab directly into the field (the Riverlab), conflating the two of them. The modelling practice is not an end to this relationship. On the contrary, it puts scientists forward to the field. The models indeed extend research questions to be asked back to the field. In other cases, the field validates the models, so the physical field is the ultimate judge. The model enables the scientists to make “sensitive tests” to know the field itself better: “there is an usual experiment in modelling practice: we carry out a simulation under these conditions, however realistic it may be, and then we carry out another simulation under other conditions where we have changed only one parameter, and we observe the impact on a variable we have examined.”[106] The practice of modelling leads scientists to question and divert the role of the model as a predictive tool in order to make it play a completely different role: that of a tool that unfolds, folds, and scripts a world and that can be perpetually modified according to a variation added and shared by the community. By detailing the objectives of a model, we became aware of the cyclical aspect of the procedure: the model pushes the scientists to new areas of research, and thus to return to the field.

The scientists follow the sulphur emissions that fall on the Vosges forest. Their practices of locally tracing global phenomena show a new articula-

105 Sylvain Kuppel, 2020.04.08
106 Idem

tion of the local/global and the landing of these terms in the Critical Zone. There is never a global perspective allowing scientists to effectively trace the phenomenon. On the contrary, once the global is mentioned, it means that they lose track of the phenomenon, either in the ocean or in the upper atmosphere where everything gets mixed up. Therefore, to measure, think, understand the CZ, scientists are local, but this local place contains many other locations. The CZO is a moment in the fluxes which are captured in real time in a specific place. The models that the scientists develop follow this moment in time, because they are "sensitivity tests", "approximations" and they always have to be rewritten according to changes in the field. Understanding, decoding, interconnecting places have not only a scientific but also a political value. Connecting the sources that cause damage to the damaged places makes it possible to demand justice, to assume responsibility.

6.6 Conclusion: Earth boundaries

Instruments are sometimes dispersed in the field. These are small devices, often of low technical complexity, installed in the field over the long term, but which do not provide direct data like the previous ones (these are gutters, nets, piezometers, etc.). These instruments are used to monitor the atmosphere in the Critical Zone. Scientists are redirecting the traditional observation of the atmosphere towards the trees and the forest to understand how the composition of the atmosphere affects it. In the process of instrumenting the forest with multiple ground-based sensing devices, the forest becomes an environment that 'feeds back' the observation, not a 'background' to be observed. This is the characteristic of what can be called an instrumented landscape that increases the convergence between the laboratory and the field by transforming the natural environment into a laboratory infrastructure and thus a sentinel of climate change. As a consequence, monitored landscapes appear as a new type of landscapes. We could ask how it could interact with a public, how it could shape new design patterns, in a close science and landscaping relationships. These could be an agenda to pursue in landscape design. The atmosphere is a living by-product, resulting from the respiration and exhalation of bacteria, trees and humans who nowadays breathe in carbon too intensively and rapidly. CZ scientists study this breathing cycle by decomposing the carbon molecule to trace its path through biotic and abiotic materials (using isotopes at the microscopic level). The boundaries between biotic and abiotic are less obvious than previously thought. Tree-related micro-organisms are among the main protagonists of this cycle. By decomposing the beings responsible for the atmosphere, scientists are overturning conventional figures of unified organisms such as trees. Trees are indeed the sentinels of a territory, they receive damage and incorporate chemicals coming from distant places. As a consequence, we should acknowledge this capacity, thus bringing a more cosmopolitical view to landscape theory: trees are not décor in a park nor an urban item in a city. However, we don't have a representation of trees which would give justice to their cosmology. And this cosmology extends deeper: by tracing the components of the atmosphere, scientists discover an unexpected atmosphere deep in the ground, like a mirror of the sky, as if the upper and lower atmosphere were connected by trees that control climate and CO_2 content. But this discovery of deep atmospheric control is not such good news: it means that current climate models do not incorporate the complexity of interactions involving CO_2 in the Critical Zone because they don't consider this huge production of CO_2 deep underground. This reiterates the need to design new visualisations that consider the complexity and unexpected (and unintentional!) behaviours of the natural entities. Lastly, in this chapter, we followed the sulphur cycle that changes the composition of the atmosphere, soil and water in a forested CZO. By linking the sources of sulphur emissions that cause damage to the places where these sulphur emissions fall, scientists are providing a new understanding of the Earth's scale, beyond state frontiers and where the 'global' is the boundary condition. In this perspective, the Earth changes, it is not a stable entity but a variation of connections, it is no longer the 'sphere' that encompasses everything. The atmosphere is therefore not 'external'. However, we lack a representation of the Earth in which we could see these planetary boundaries, but also the connections from a territory to another, in a single frame of reference, in order to understand how the global is shaped. Indeed, we don't have a visualisation that is not human focused. We should design one that acknowledges all the other cycles, engendered by trees, organisms, inorganic matters, etc, so that we could see the continuity be tween the entities, but also their clashes or bifurcations when interrupted by a perturbator agent. This is needed because through the study of cycles, decisions and responsibilities (who pollutes whom?) may be traced, which can ultimately make cosmopolitics possible.

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7 Mapping the Critical Zone

The aim of this chapter is to translate the findings of the fieldwork in the Critical Zone into useful findings for the field of architecture. In this chapter, we will expose how we contribute to the field of architecture with new visualisations based on the findings of the empirical chapters. We will ask: how do these visualisations, different from others, propose alternative theorisations of territory and landscapes? How does this study allow for a different and more in-depth understanding of climate issues? And where will this lead us in the field of architecture?

7.1 A lack of non-anthropocentric representations

In the literature review, we have highlighted the blind spots of anthropocentric theories, approaches and representations of the environment. Most of the current cartographic techniques and architectural projections which are used derive from an anthropocentric view (Olwig, 2008; Grevsmühl, 2014; 2016; Brotton, 2013). On the one hand, perspective, which is essential in design communication, is used to provide a virtual image of the design project. Created during the Renaissance (Farinelli, 2009), perspective is a view centred on the human subject. On the other hand, technical drawings, axonometric drawings, plans, and sections inherited from industry and widely used in design projects, separate each part of a whole as if it were a machine. The problem is that these types of drawings are used to design parks or plan cities, thus spreading functional and human oriented urbanism. Cartographies, maps of a territory, were originally designed to describe the obstacles of a terrain and to trap possible enemies on the battlefield (Lacoste, 2014). They are the result of a long history of territorial conquest, war and colonisation.

According to the findings of the previous empirical chapters, it appears difficult to describe the Critical Zone from the anthropocentric point of view where entities are taken for granted (da Cunha, 2018). The soil is considered as a stable surface with no depth on which to build. The river is a resource and appears as a line to be managed. The atmosphere is located 'out there'. A tree is a green dot on the surface map, an ornament; at best it is an object providing an ecosystem service. Other mapping approaches are less anthropocentric but still problematic. For example, in *The map of disputes, in France* **(Fig.98)**, the centre of the image is a piece of land, a forest, for example, represented from the different points of view of those who claim rights over that piece of land. Even if the map encompasses several points of view, it is intended for human appropriation and does not represent the view of the forest itself.

Fig.98. Ancient map called 'Figures accordées'
Map of dispute over territories. Figure de la garde de Lymeux dans la forêt de Breteuil (Eure), 1565. *Quand les artistes dessinaient les cartes. Vues et figures de l'espace français.*

Another interesting representation is *the Kircher's map of the cosmos* **(Fig.99)**. Here there is no point of view but only phenomena that tear the earth apart in its depths. The problem is that we do not know where we are, what these phenomena are and how we can observe them. It is therefore more an image than a map (that would provide orientation and description of a territory).

This lack of accurate representation leads to an inaccurate understanding of Earth processes and their complexity. The CZ indeed challenges conventional representations of the environment. Compared to what we witness in the CZ, the anthropocentric representations lack of *variability* – there is only one way for the river to be, as well as *heterogeneity* – the same rep-

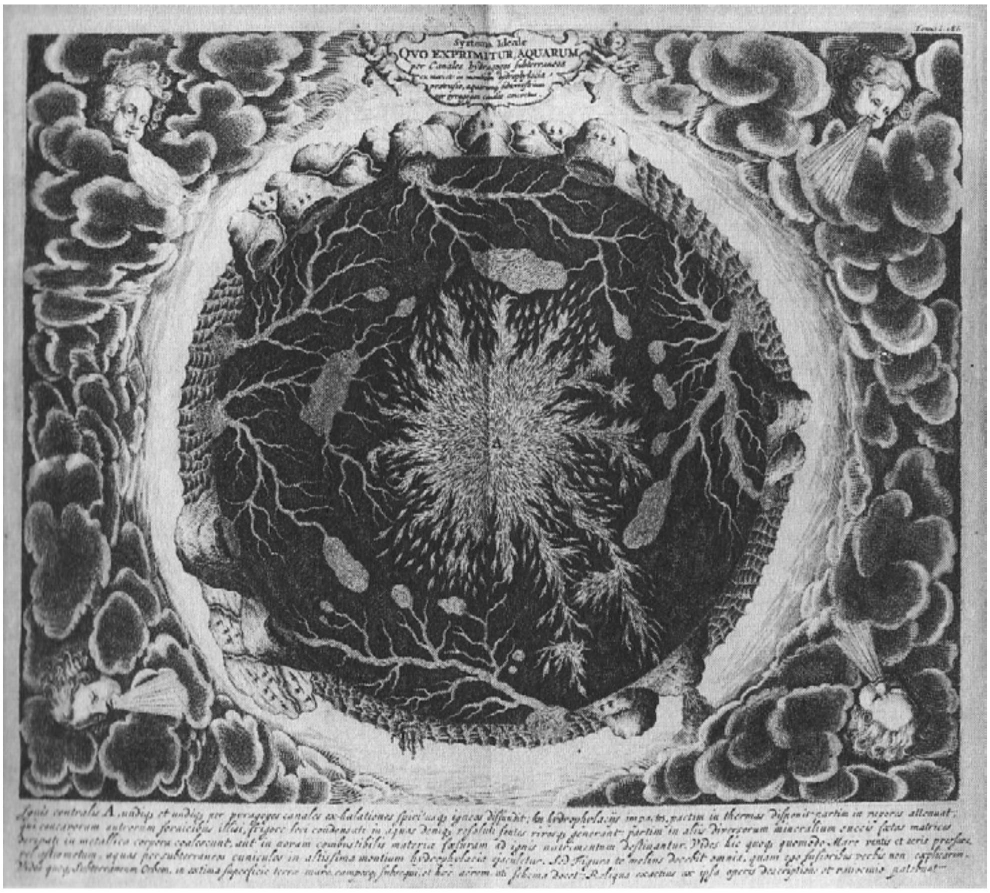


Fig.99. Kircher's map of the interior of the earth
Athanasius Kircher, *Interior of the earth*, 1678. The map shows subterranean lakes, rivers and fire pools: a dynamic Earth and connections across the depths.

resentation of the river is used for any river at any place, and *agency* – the river is an element of the background. This is even more true for the soil. On maps, the qualities of the soil at different depths and its interactions with other organisms and elements are invisible because the map's point of view is from above. The soil is simply the surface on the map; it does not move—or is moved to build (excavation). The atmosphere is even less visible because the connection with the trees that literally make it are not visible. It is not only that we lack the theoretical approach, but we also do not have the graphic tools to draw how these entities behave and shape the environment. We can argue that these two shortcomings are linked. The problem is that it seems that these entities are thought of as if they could last forever, that human activities are superimposed on a background of entities that do not react to our actions. However, in the Anthropocene human activities are causing these entities to change at a rapid pace: soils, rivers or the atmosphere are shifting and disappearing, or their composition is changing, the result being a change of the whole environment and the conditions of habitability for all living beings. However, we cannot observe these changes in the maps. While these maps set boundaries to territories, in the CZ what characterises territories is interconnection through phenomena that scientists describe as cycles.

The problem that concerns us is that the oversimplification of cartographies leads to climate scepticism, indifference or simply lack of understanding of the situation. This is because the entities and their behaviours, their agencies, and the risks they face are not reflected in our representations; their complexity is not taken into account. Not understanding this complexity and not having the right representations leads to underestimating the seriousness of these issues and therefore leads to reactions like climate scepticism, indifference or other types of attitudes towards climate change that we are witnessing at the moment. This last chapter addresses the crisis of the environment through the crisis of its representation, as if the two problems were in fact two sides of the same coin. This is why it is important to develop different representations in which nature is not passive, where we can see the complexity with our own eyes, and thus be able to understand, to grasp our responsibility to act.

7.2 The Critical Zone mapping experiment

This thesis attempts to provide answers by following the scientists at work to understand each entity and bring this knowledge back to the field of architecture. One way to do this is to draw alternative mappings. The ethnographic methodology that is used in the empirical chapters brings new material to the discussion. Ethnographic observations offer the chance to be present at the right time in this troubled period and to witness the advances in knowledge of the Critical Zone. How can this ethnographic work be translated into different cartographies and visuals that would better communicate the gravity of the climate issue? And which, as a result, could trigger different types of action by designers?

Alternative visualisations become possible by spending time exploring the water, soil or the atmosphere, and slowly following the practices of scientists in the CZ. This fieldwork, this monitoring, is necessary because the scientists in the CZ have the instruments and the terrain (the observatories) to better understand the earth processes. The resulting type of knowledge expands a previously too limited view of natural entities. In the empirical chapters, we have described what scientists are tracing in order to bring this knowledge back into the field of architecture to better understand what we call the Earth. The CZ findings provide a new understanding of the composition of natural entities: soil is porous, it is granular material with water around it, it is unstable and it varies in depth; the river is plural, it is multiple in its composition and thickness; the atmosphere is partially inside the living beings and interacts at the scale of the Earth. In this chapter we will explore the translation of this knowledge into a cartographic representation different from the one we are used to. We ask ourselves what the limits of cartography are and where we should focus instead. This leads to new questions about 1.the *Soil:* how to give depth to the surface? 2.the *river:* how to trace the different water paths and their components? 3.the *atmosphere:* how to make the atmosphere and its components visible? Overall, the aim is to show the composition of each entity.

The empirical chapters have shown how disturbances, climate issues and the Anthropocene are treated by scientists. Here we will present a first alternative map, which is based on the knowledge of the CZ and what can be learned from it. Visualisation is indeed important in the development of knowledge, and the skills of architects are also intended to reorganise the world, to recreate the cosmos, slowing down chaos, working to hierarchies beings and allowing them to live together (Grosz, 2008). How then can the knowledge of the CZ be translated into a different cartographic representation? Conversely, what can we, as architectural researchers, bring to the work on the Critical Zone?

The map of the Strengbach CZO

<u>A change of frame of reference</u>

As we saw in the Literature Review, maps using the latitude and longitude grid projection are drawn as if the eyes were above, floating in the universe (Nagel, 1986). The deep ground and atmosphere (a vacuum escaping into the distant space above the Earth) are excluded from this projection. The alternative projection proposed in this chapter accomplishes a conceptual revolution in the way we understand the Earth **(Fig.100)**. We have seen in the chapter on soil that the soil is constantly formed by erosion and weathering as a function of deep processes. It is an unknown, porous, connected world. The alternative map that is presented here therefore shows these layers of the soil as in a cross-section **(Fig.101)**.

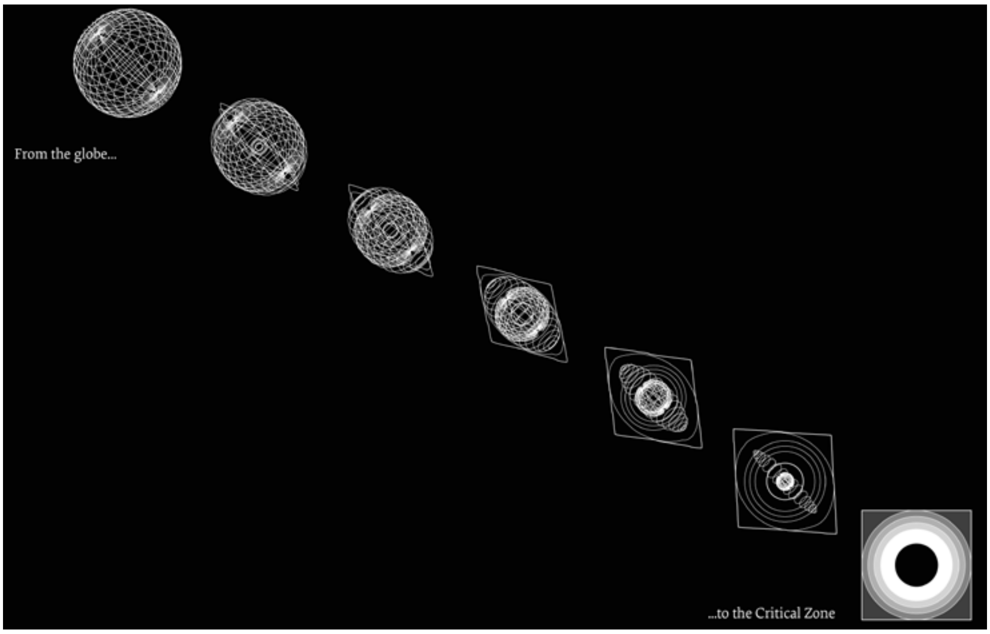


Fig.100. From the Globe to the Critical Zone
A conceptual revolution in the way we understand the Earth. Drawing by the author.

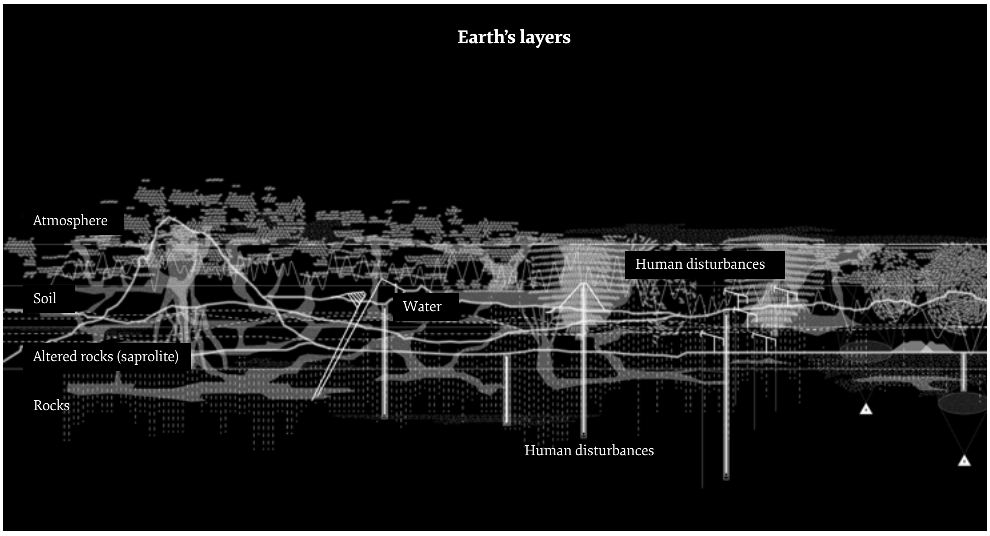


Fig.101. Cross section of the CZ layers
Cross-section of the Critical Zone showing the Earth layers. Drawing by the author.

However, a simple cross section would not render the rounded curve of the Earth and its closure. This can be achieved by arranging these provisional layers of the cross section in nested circles. Intuitively, one would arrange the deep rocks in the inner circle and the atmosphere in the outer circle, referring to the structure of the planet **(Fig.102)**. Here there is an inversion of these layers in order to enclose the atmosphere in the middle (we will understand why later). The rocks are placed on the outer circle and the atmosphere on the inner circle. The soil remains in the middle, at the interface of the rocks and the atmosphere **(Fig.103)**. The Earth seems to be reversed as if were a glove turned inside out **(Fig.104)**. Therefore, the visualisation doesn't map the surface and the visible, but inverts the gaze in order to visualise the subsurface and further down to the depths where the atmosphere and water react with the rocks and transform them into soft soil. The soil is here more visible, more central on the map. The human-centred frame of reference has been overturned.

We have seen in the chapter on atmosphere that pollutants carried by the atmosphere remain in the ozone layers, are transported, and eventually fall back on Earth somewhere. On the alternative map suggested, the atmosphere is visualised as an enclosed space, not infinite and directionless. The atmosphere in the centre of the projection emphasises the fact that its content is trapped in the ozone layers: atmospheric pollution does not disappear into space but returns to us on Earth **(Fig.105)**. Placing the atmosphere in the centre reinforces the idea that there are terrestrial boundaries, that the pollutants that are released into the atmosphere, such as CO_2, sulphur or nitrogen, do not escape into the infinite universe but remain there, trapped within the boundaries of the planet.

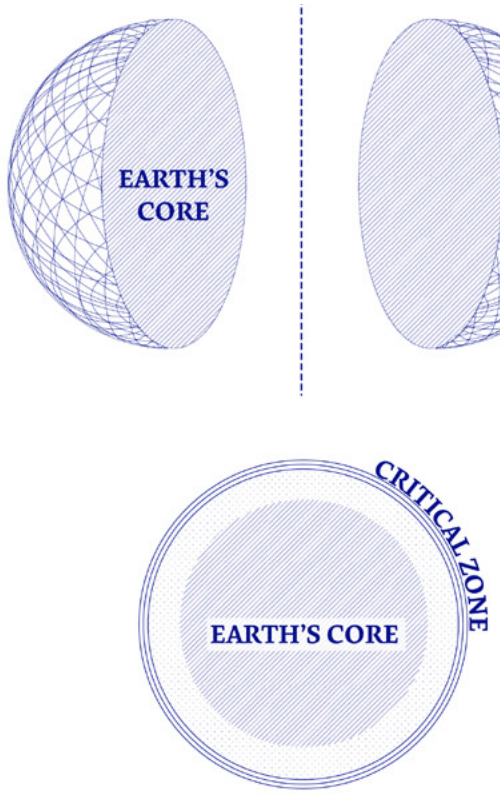


Fig.102. Mapping the CZ, step 1

The cross-section of the Earth as it is in the structure of the planet. Drawing by the author.

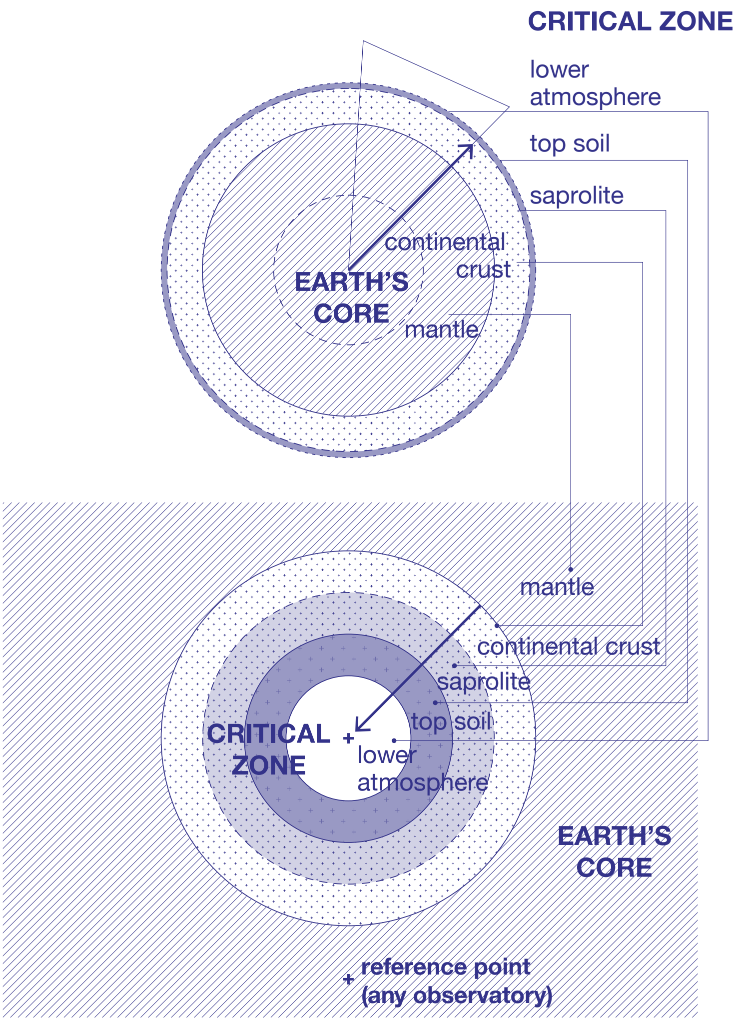


Fig.103. Mapping the CZ, step 2

Recomposing of the Earth layers with soils at the centre. The first steps of the construction of the projection: reversing the Earth's skin in order to give more space to the soils, this thin layer which is invisible at the planetary scale and yet primordial for life. Focusing on a specific place, on an observatory, we can measure precisely the depths of each vertical layer (lower atmosphere, canopy, soil, weathered rocks). Drawing by the author.

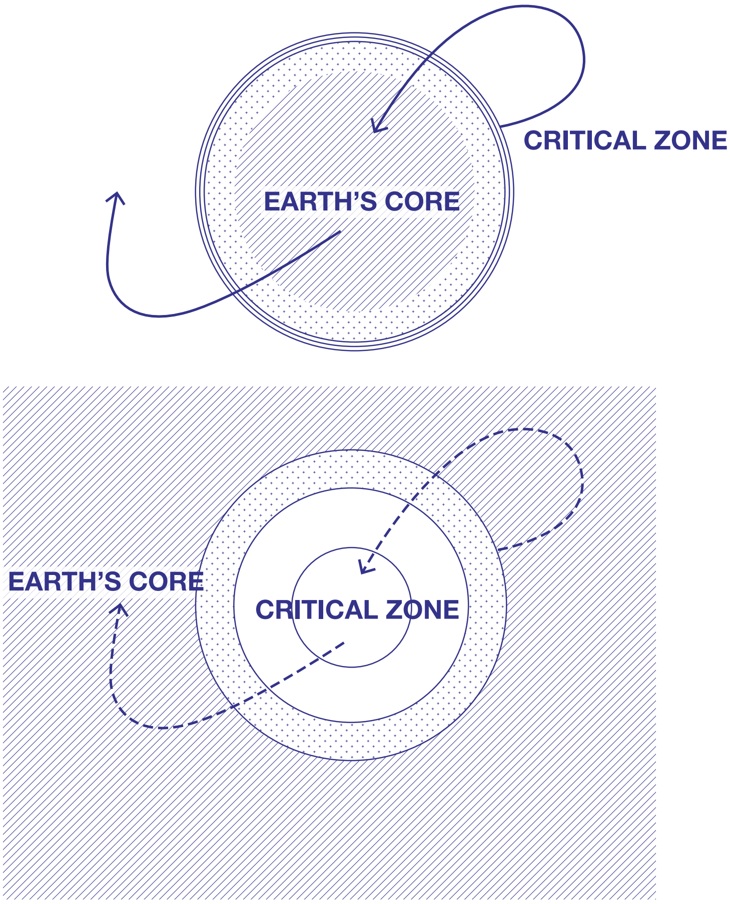


Fig.104. "The glove operation".

Turning the Earth inside/out to give depth to the surface. Drawing by the author.

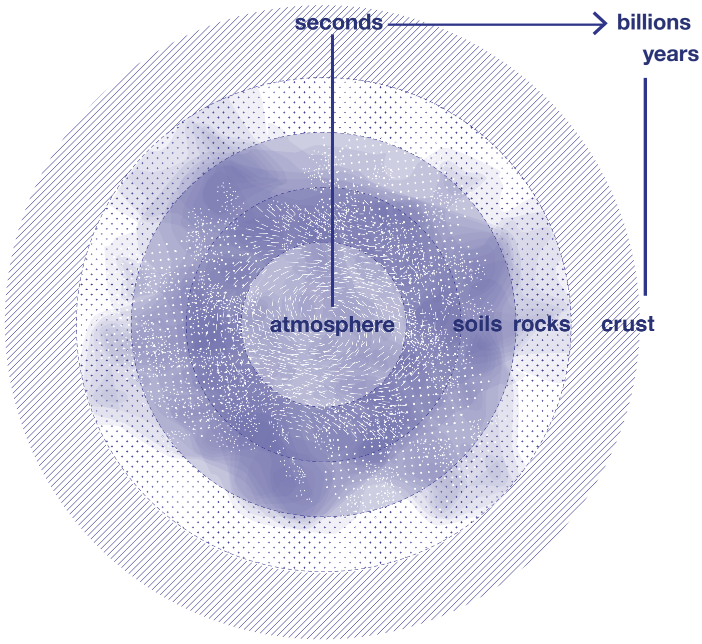


Fig.105. Enclosing the atmopshere

Soil-atmosphere coupling: the pollution is kept inside. This projection makes it possible to visualize the concentrated and cyclic pollution in the atmosphere. Each circle (layer) also corresponds to temporal phenomena: in the atmosphere, the circulation of chemical elements takes a short time, whereas in deep rocks, the cycle takes longer to complete. Drawing by the author.

What we have seen in the empirical chapters is represented in the map: the instruments, the procedures from the field to the lab work, and the phenomena. Based on the projection described before, a map of the Strengbach CZO is produced (Fig. 121). It translates the results of this observatory into an alternative visualisation of a territory to better reflect what is happening in the Critical Zone. The map visualises the Critical Zone of the Strengbach observatory using the ethnographic materials gathered during the fieldwork and the analyses of the empirical chapters. Interactions with the scientists (interviews, ethnographic observations), access to their data (photos, diagrams, papers, microscopic view, etc), access to the field (location of the instrumented stations, information on the instruments, practices and manipulations of the scientists) (Fig. 106), and the lab (procedures, machines, models, etc) are the resources for this map. The following is a list of items borrowed from the scientists' data.

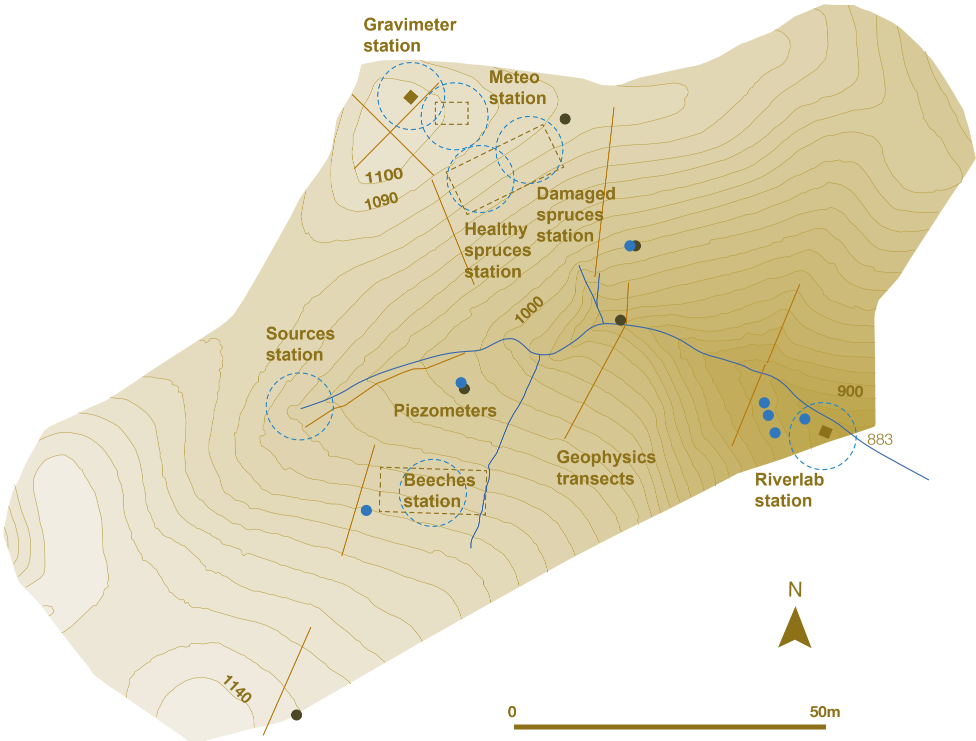


Fig.106. Map of the Strengbach CZO

Map of the Strengbach Critical Zone Observatory with the instrumented stations. Drawing by the author.

- Microscopic imageries of sediments of the river **(Fig.107)**
- Schemes of granite rocks and fractures drawings **(Fig.108)**
- Microscopic imageries of rock's chemical contents **(Fig.109)**
- Accurate reading of the rock's characteristic of an 80-metre depth core sample **(Fig.110, 111 & 112)**
- Chronicles of weather patterns: rains, winds, temperature records **(Fig.113)**, and chronicles of the water flux at the outlet **(Fig.114)**
- Chronicles of the amount of sulphur in rain, trees, soil, and river over 30 years **(Fig.115)**
- Maps of geology **(Fig.116)**, groundwater recharge at the source **(Fig.17)** and water path at the surface of the watershed **(Fig.118)**
- Graphs of gravimetric groundwater evolution over a year (see chapter 1)
- Geosesmic readings: eight 100m long cut sections across the watershed from 0 to 150m depth showing the gradient of porosity of the soil (where there are rocks and when it becomes soft soil) **(Fig.119)**
- A long cut section across the entire watershed showing the situation of the piezometers: their depth, their record of water and their record of the quality of soil (sand, weathered, solid)

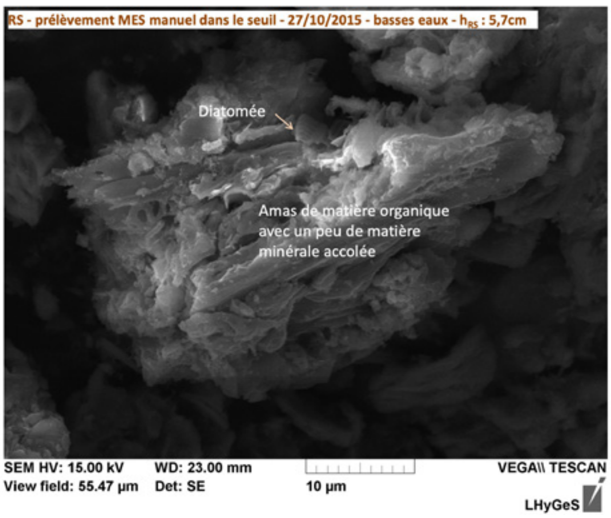


Fig.107. Microscope sediments
Microscopic imageries of sediments of the river, Strengbach CZO. Image given by Solenn Cotel, OHGE.

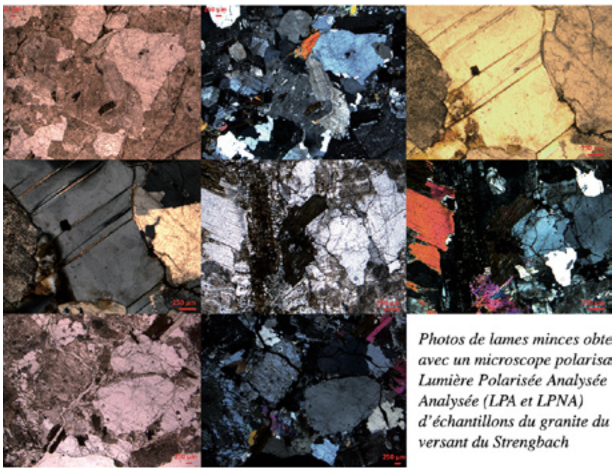


Fig.108. Microscope granite

Microscopic imageries of granite rocks, Strengbach CZO. Image given by Marie-Claire Pierret, OHGE.

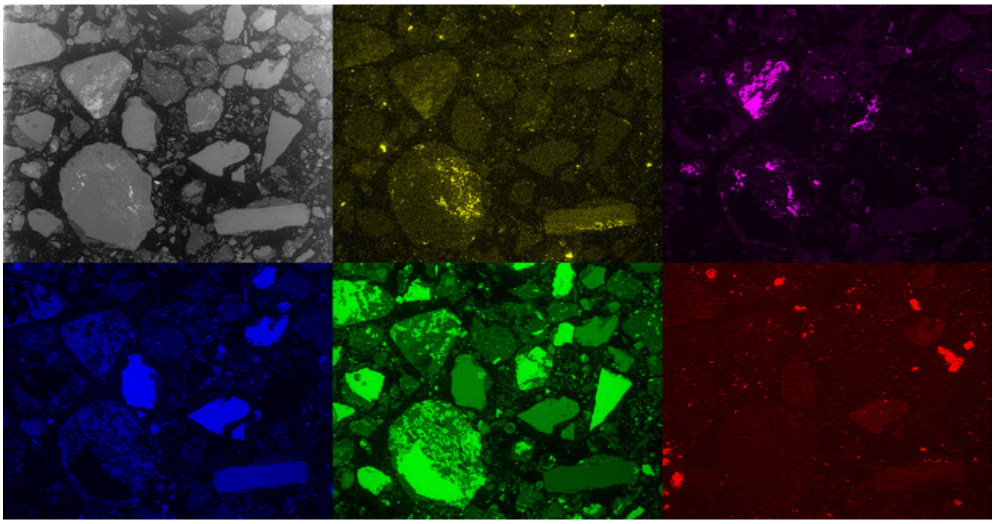


Fig.109. Microscope chemicals

Scanning Electron Microscopy (SEM) images of a soil sample from a spruce plot in the Strengbach watershed. The different colours correspond to the areas of concentration of different elements (yellow: titanium, violet: iron, blue: potassium, green: silica, red: sodium). Image credits MEB-LHYGES, Strasbourg. Image given by Marie-Claire Pierret, OHGE.

Fig.110. Zoom on a core sample

Photography of one meter of the 80 metres depth core sample showing granite rock and fractures allowing water to penetrate at depth. Image given by Marie-Claire Pierret, OHGE.

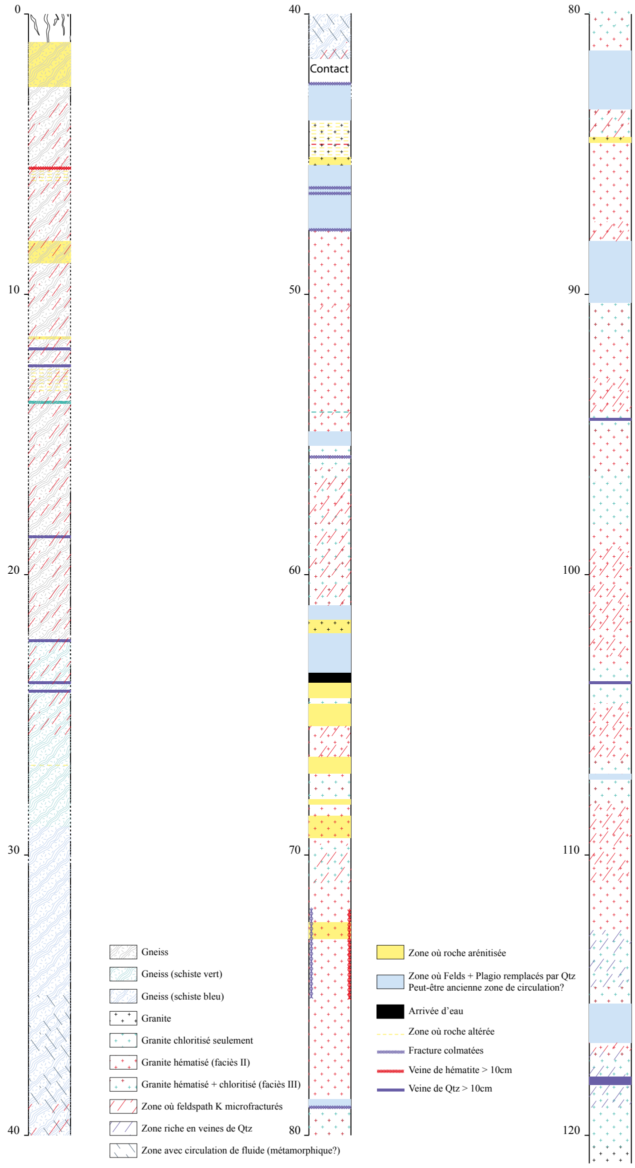


Fig.111. Diagram of the core sample

Accurate reading of the rock's characteristic of an 80 metres depth core sample, Strengbach CZO. Image given by Marie-Claire Pierret, OHGE.

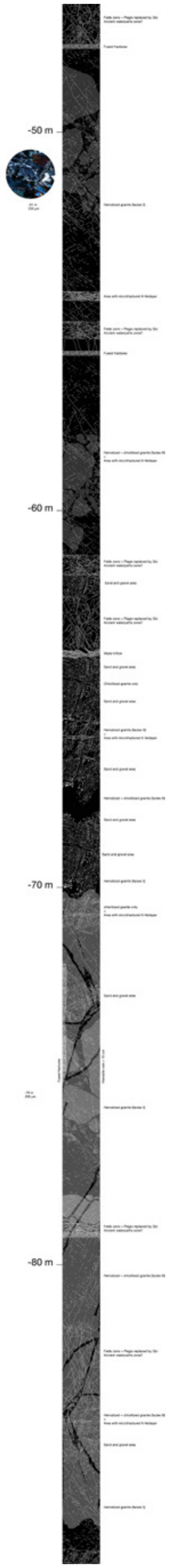


Fig.112. Borehole

Drawing of the same 80 metres depth core sample by the author.

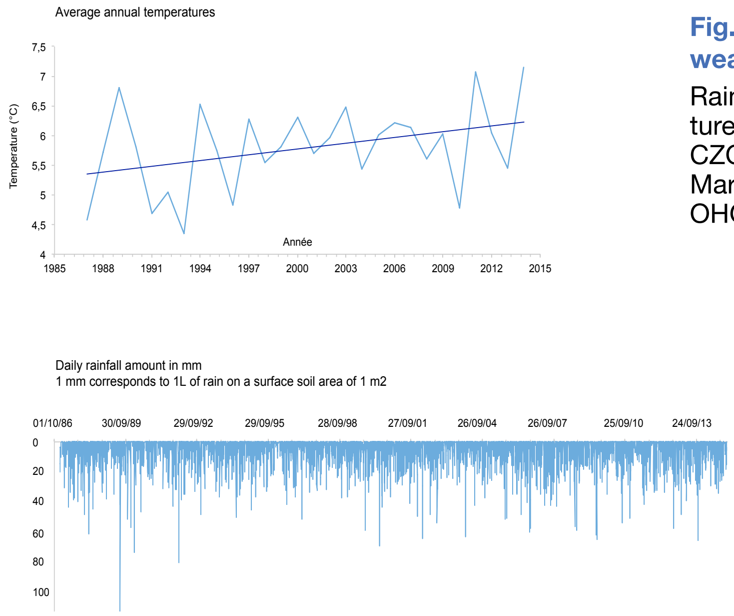


Fig.113. Chronicles of weather patterns

Rains, winds, temperature records, Strengbach CZO. Image given by Marie-Claire Pierret, OHGE.

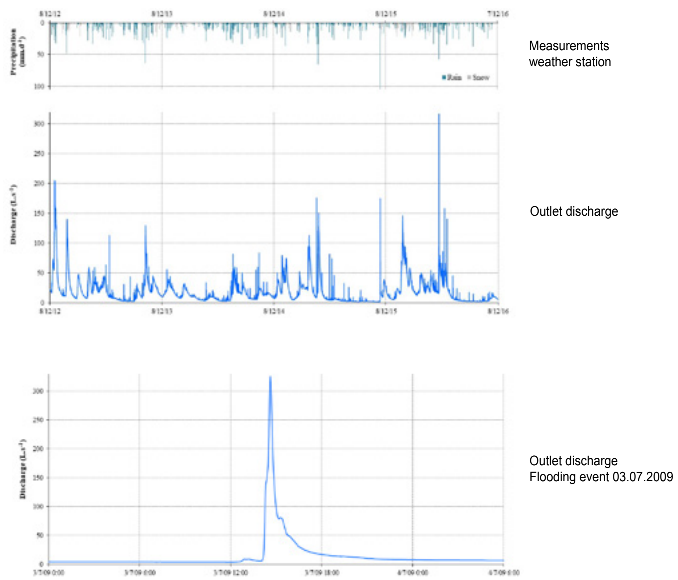
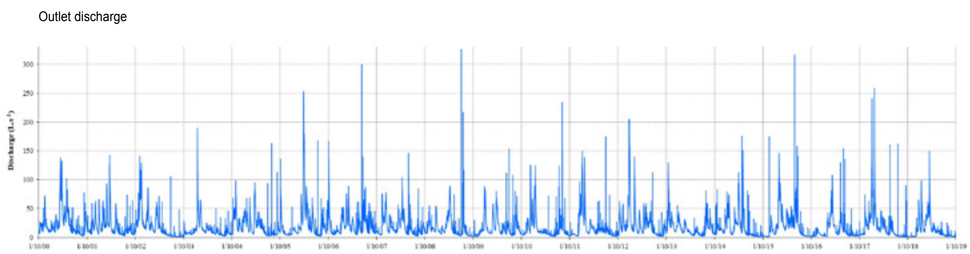
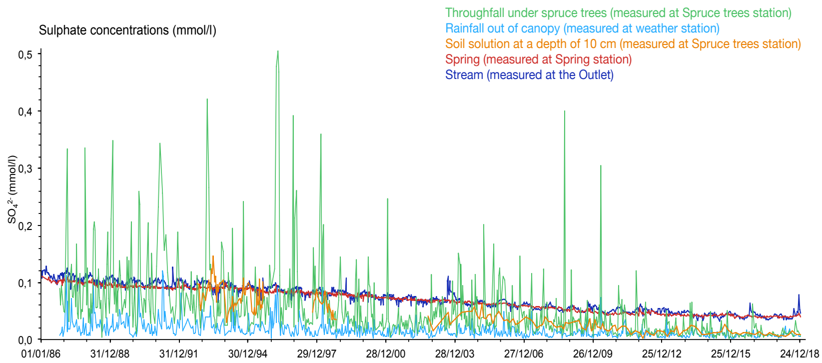
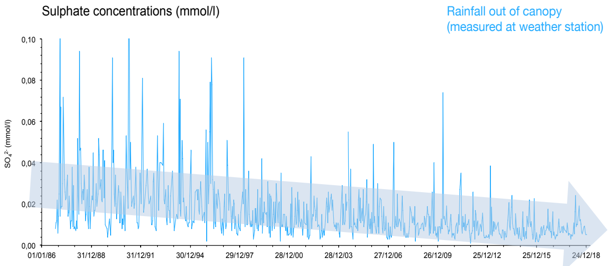


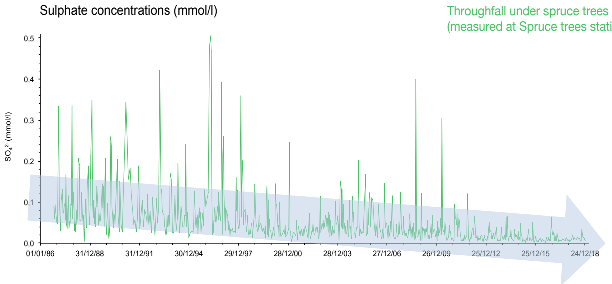
Fig.114. Chronicles of the discharge water flux

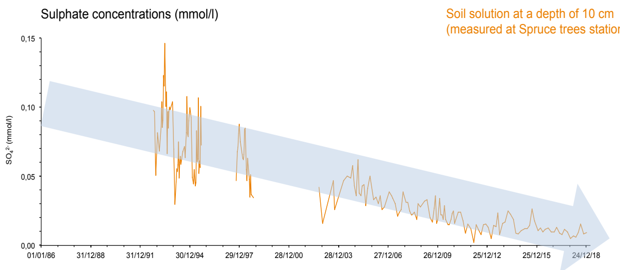
Measures at the outlet of the river, Strengbach CZO. Image given by Solenn Cotel, OHGE.











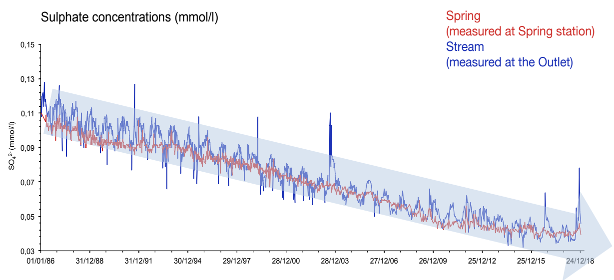


Fig.115. Chronicles of Sulphur

Amount content in rain, trees, soil, and river over 30 years, Strengbach CZO. Image given by Marie-Claire Pierret, OHGE.

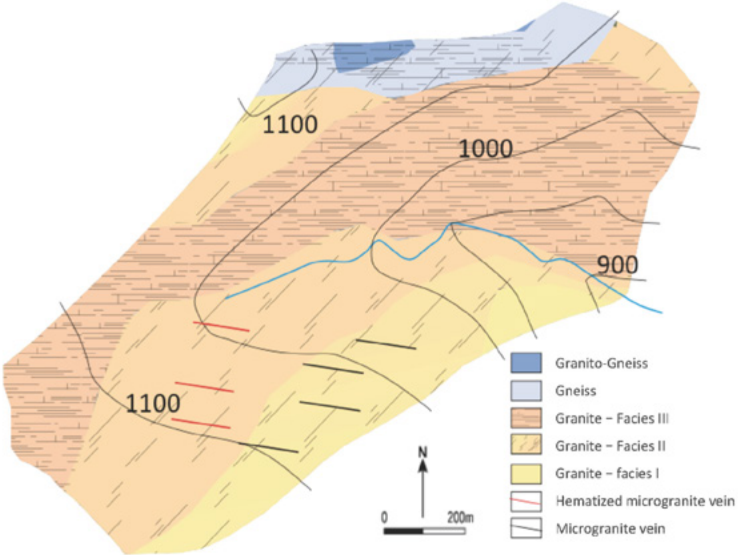


Fig. 3. Geological map of the Strengbach catchment.

Fig.116. Geological map

Strengbach CZO. Image given by Marie-Claire Pierret, OHGE.

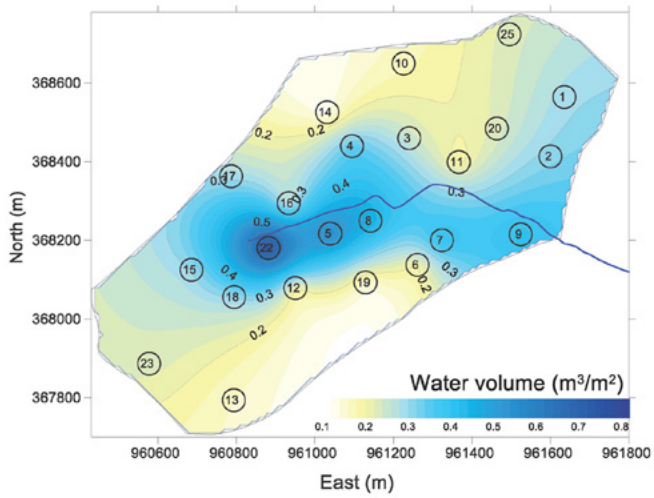


Fig. 10. Map of the magnetic resonance sounding water column (water volume per surface unit), which is an indicator of saturated alterite thickness, interpolated across the whole catchment.

Fig.117. Water storage map

Map of the water volume at depth, Strengbach CZO. Image given by Nolwenn Lesparre, OHGE.

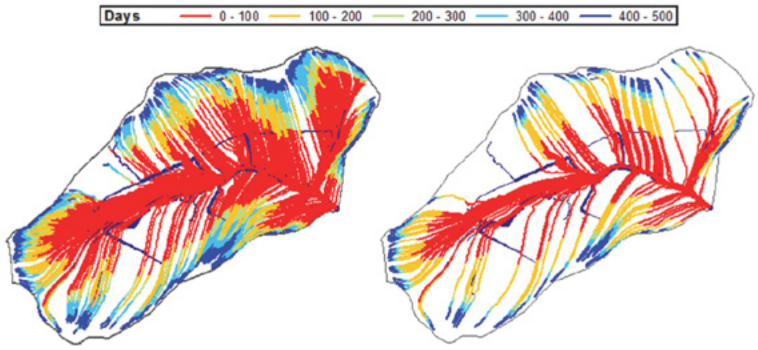


Fig. 9. Streamlines of the subsurface water contributing to the surface drainage network on 1 Mar. 2010 (left) and 1 July 2010 (right). The color scale denotes that a water particle reaching the river on a given date (e.g., 1 March) started its path along the streamline or passed at a given location along the streamline *x* days prior. The density of streamlines is associated with the flowing vs. dry fraction of the river network for a prescribed date.

Fig.118. Map of waterpaths

Map of water paths on the surface, Strengbach CZO. Image given by Nolwenn Lesparre, OHGE.

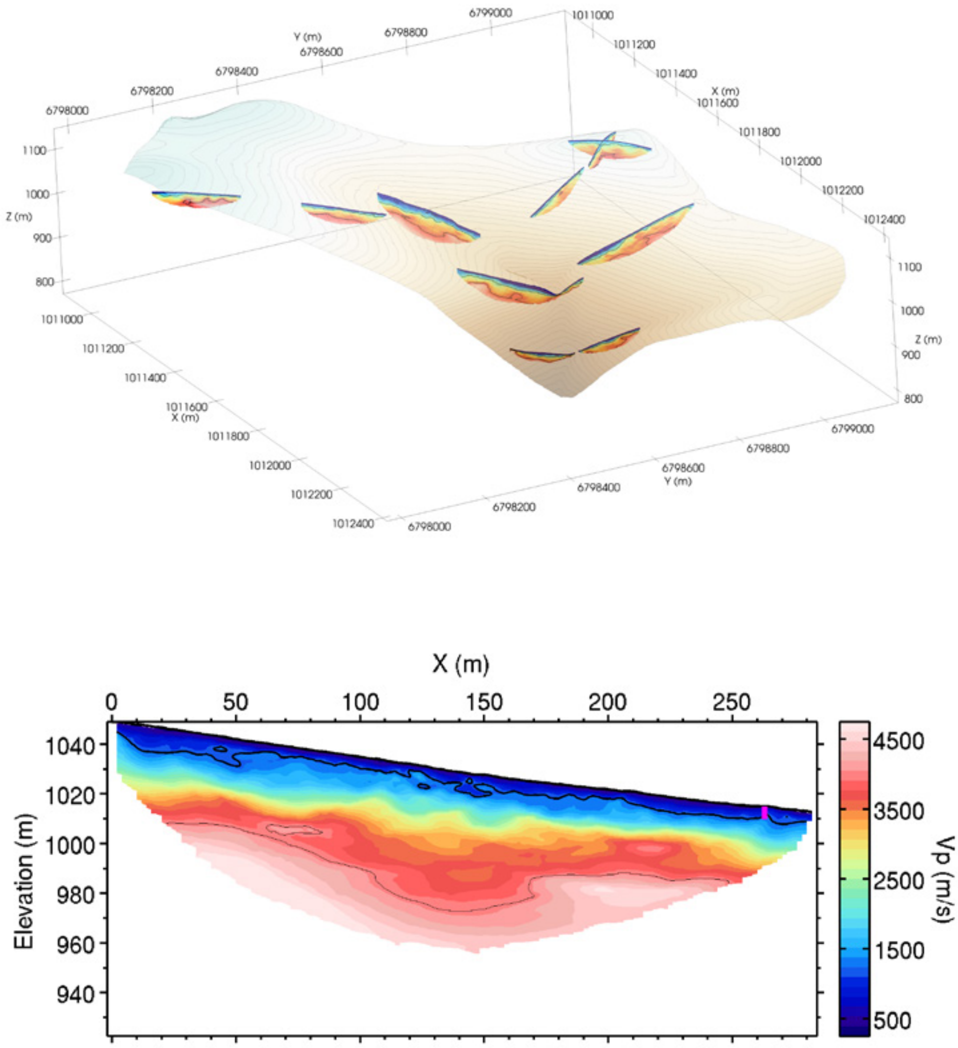


Fig.119. Geophysics cross section

Geosesmic readings: eight 100m long cut sections across the watershed from 0 to 150m depth showing the gradient of porosity of the soil (where there are rocks and when it becomes soft soil), Strengbach CZO. Images given and drawn by Sylvain Pasquet.

This projection abandons the satellite view in favour of the CZ instruments that are deployed on the ground. On the map of the Strengbach CZO, the blue features are the scientists' instruments currently located at the observatory **(Fig. 120)**. These are the same instruments that we have seen in chapters 4, 5 and 6, where we came to understood what they were used for. These instruments are considered part of the visualisation. Each instrument observes and measures a particular characteristic of the Strengbach Critical Zone: soil porosity, river chemistry, atmospheric composition. The map gathers the observations of the instruments and distributes this knowledge through the projection **(Fig. 121)**.

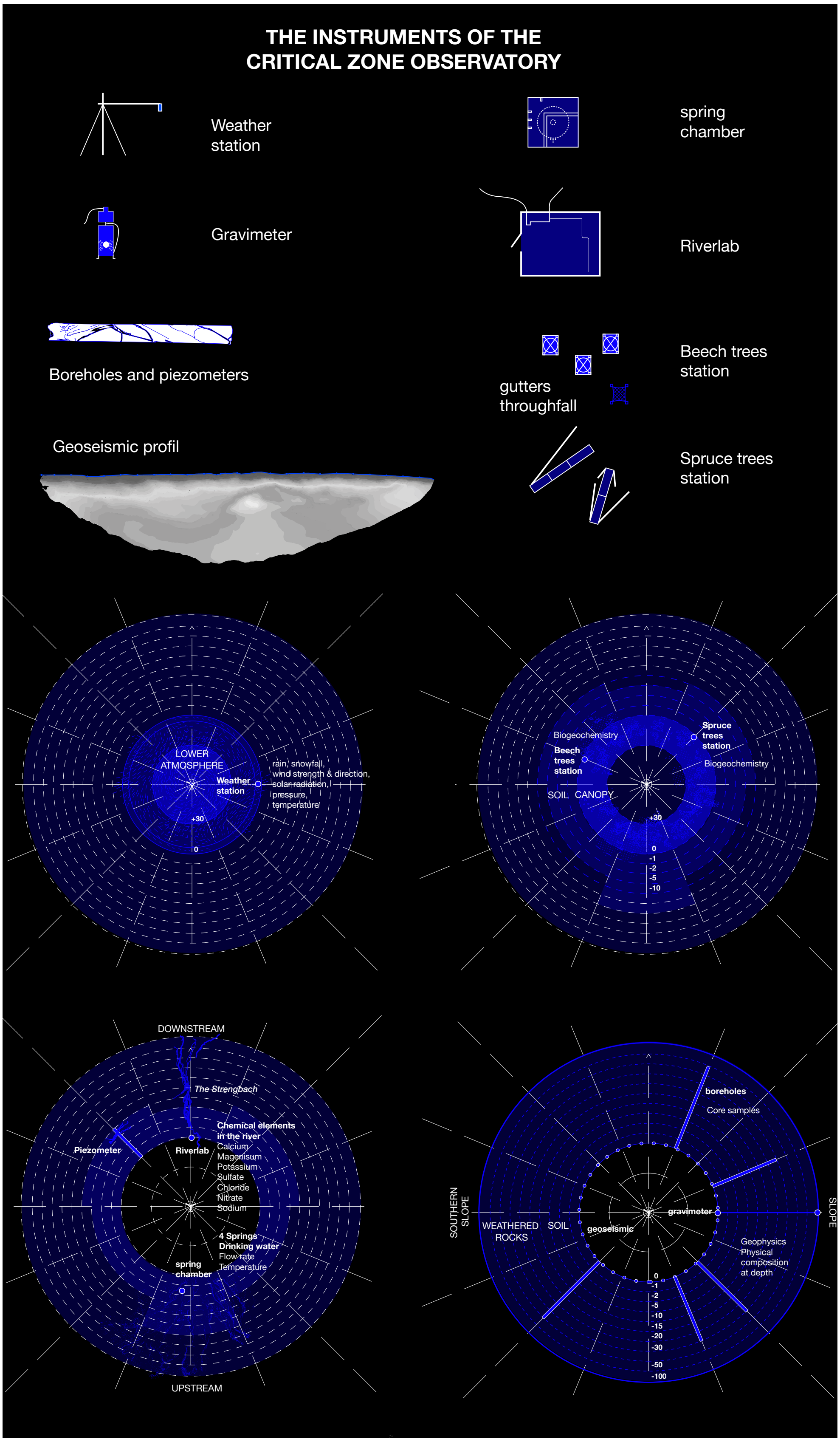
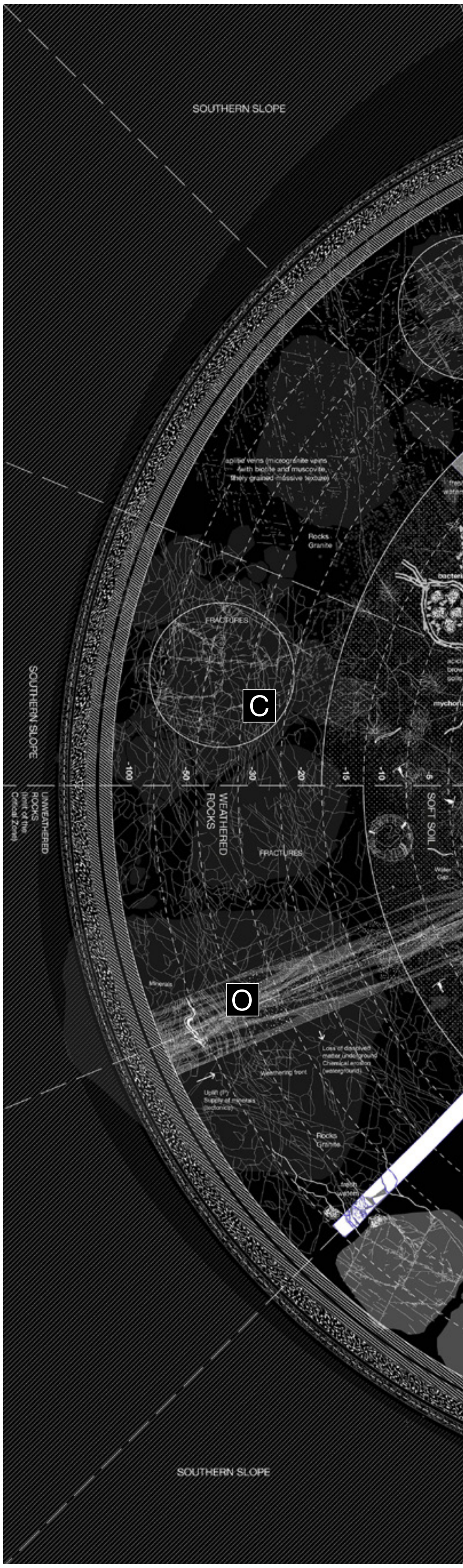
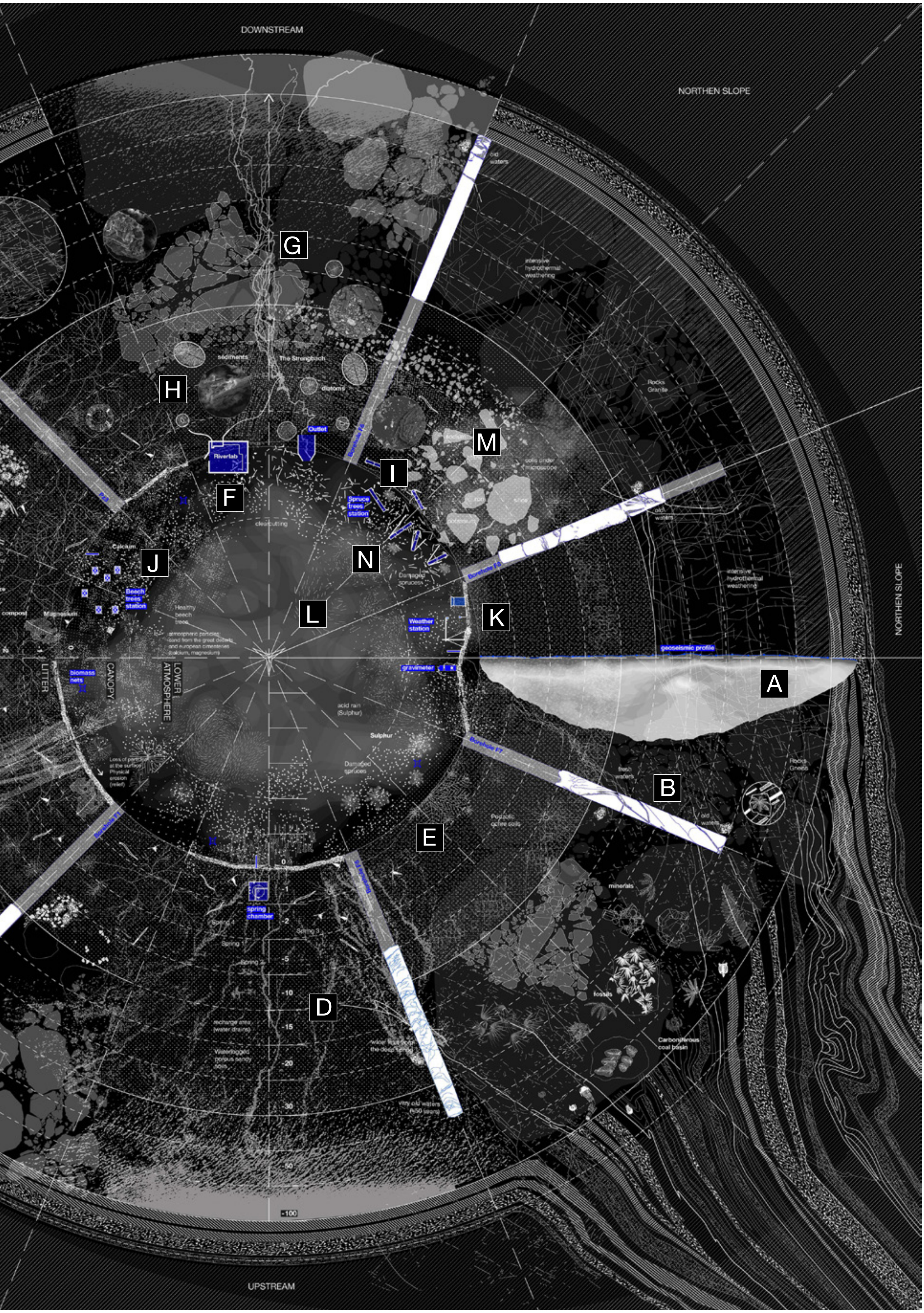


Fig.120. The Instruments reported on the CZO map

The instruments and their situation in the Critical Zone of the Strengbach CZO. Drawing by the author.

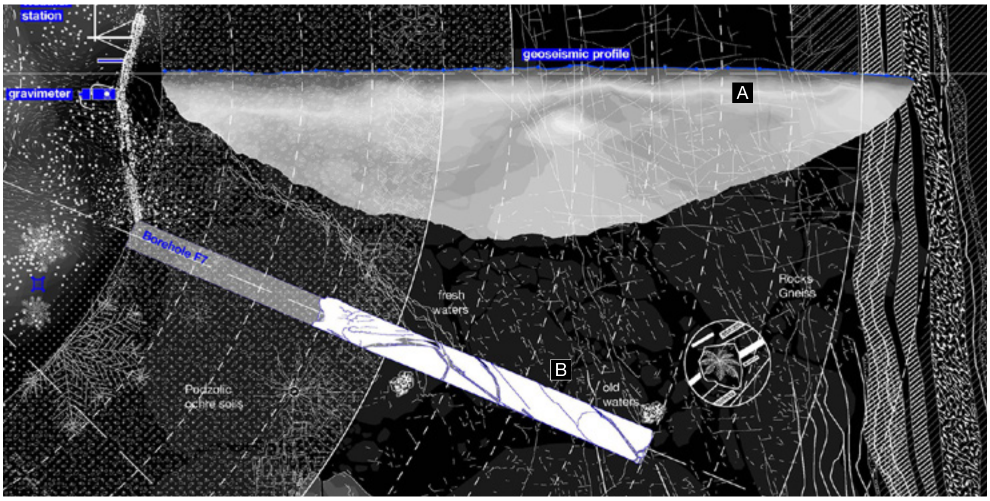
Fig.121: The SOIL map of the Strengbach CZO
Drawing by the author.




DOWNSTREAM
NORTHEN SLOPE
G
H
M
I
F
J
N
L
K
A
B
E
D
sediments
The Strengbach
diatoms
Outlet
Riverlab
Spruce trees station
Beech trees station
Weather station
gravimeter
geoseismic profile
biomass nets
spring chamber
LITTER
CANOPY
LOWER ATMOSPHERE
clearcutting
Calcium
Magnesium
compost
Healthy beech trees
Damaged spruces
acid rain (Sulphur)
Sulphur
Rocks Granite
intensive hydrothermal weathering
old waters
fresh waters
minerals
fossils
Carboniferous coal basin
very old waters
-100
UPSTREAM

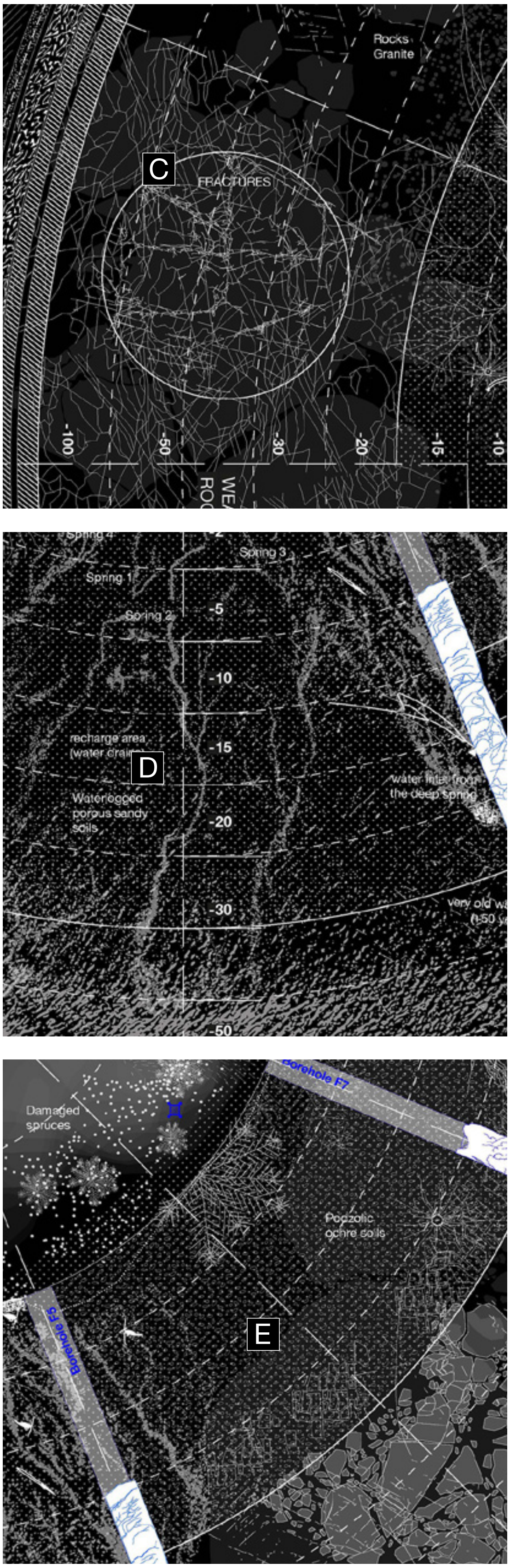
The boreholes and geophysics

In the chapter on soil, we have seen the geoseismic techniques with geophones **(Fig. 122 - A)** and core extractions **(B)** that scientists use to overcome the blindness of soil observation. We have shown that the near-surface is the site of important interactions, that the soil is porous, fractured, composite and permeable to water. In the visualisation, we can see these fractured granite blocks **(C)**, visible with geophysical tools. Fractures are faults through which water flows at depth, the flow paths shown on the map, slowly rising and gathering towards the source **(D)**. We also explained that the soil is not homogeneous, and that erosion and weathering processes make up the soft soil. Therefore, we see this composition on the map, where the deep soil varies from solid blocks to sandy material **(E)**.



Geoseismic (A) and boreholes (B)

Fig.122. Zooms in the CZO map showing the 'deep' stations



Granite (C), waterpaths (D) and sand (E)

The Riverlab

In the chapter on rivers we encountered the Riverlab, an architectural instrument that captures the many rivers - the many elements that make up a river, the result being we can say that the river is a pluriverse. The river is not one, each elementary river playing its own melody. On the map, the Riverlab **(Fig.123 - F)** and the many rivers **(G)** are shown, as are the microscopic actions that this lab in the field allows us to see in the river **(H)**. We also see that the Riverlab is one of the many instruments and technologies used by scientists to account for the complexity, cycles and composite nature of the Earth.

The gutters

In the chapter on atmosphere we have observed how the gutters placed under the trees allow scientists to understand the composition of the atmosphere and to follow its movements through the weather station. These instruments are placed on the map in three different stations (spruce **I**, beech **J**, weather **K**). Also shown on the map are the sulphur particles from the atmosphere **(L)** that seep into the soil **(M)** through the tree canopy **(N)**. As we have seen, the atmosphere is ephemeral, short-lived and we move directly through it, ingesting, inhaling and exhaling it. Therefore, the atmosphere is actually at the centre of the visualisation with the tree canopy around it. And it is also in the soil, as atmospherically-derived carbon seeps in and is sequestered in carbon-containing compounds deep down, like a mirror of the atmosphere at the surface.

This alternative map involves new mapping procedures that can be reproduced. As a result of the representation all of the scientific instruments, all the entities - soil, river, atmosphere - are superimposed in the map. This certainly creates a complexity of reading, but the visualisation codes introduced in the map make it possible to organise this complexity with the various cartographic reference systems suggested: structure, hierarchy of elements, legends, scales, metrics, transparency effects, etc.

The orientation

North is no longer the referent for orientation. Instead the sign in the middle of

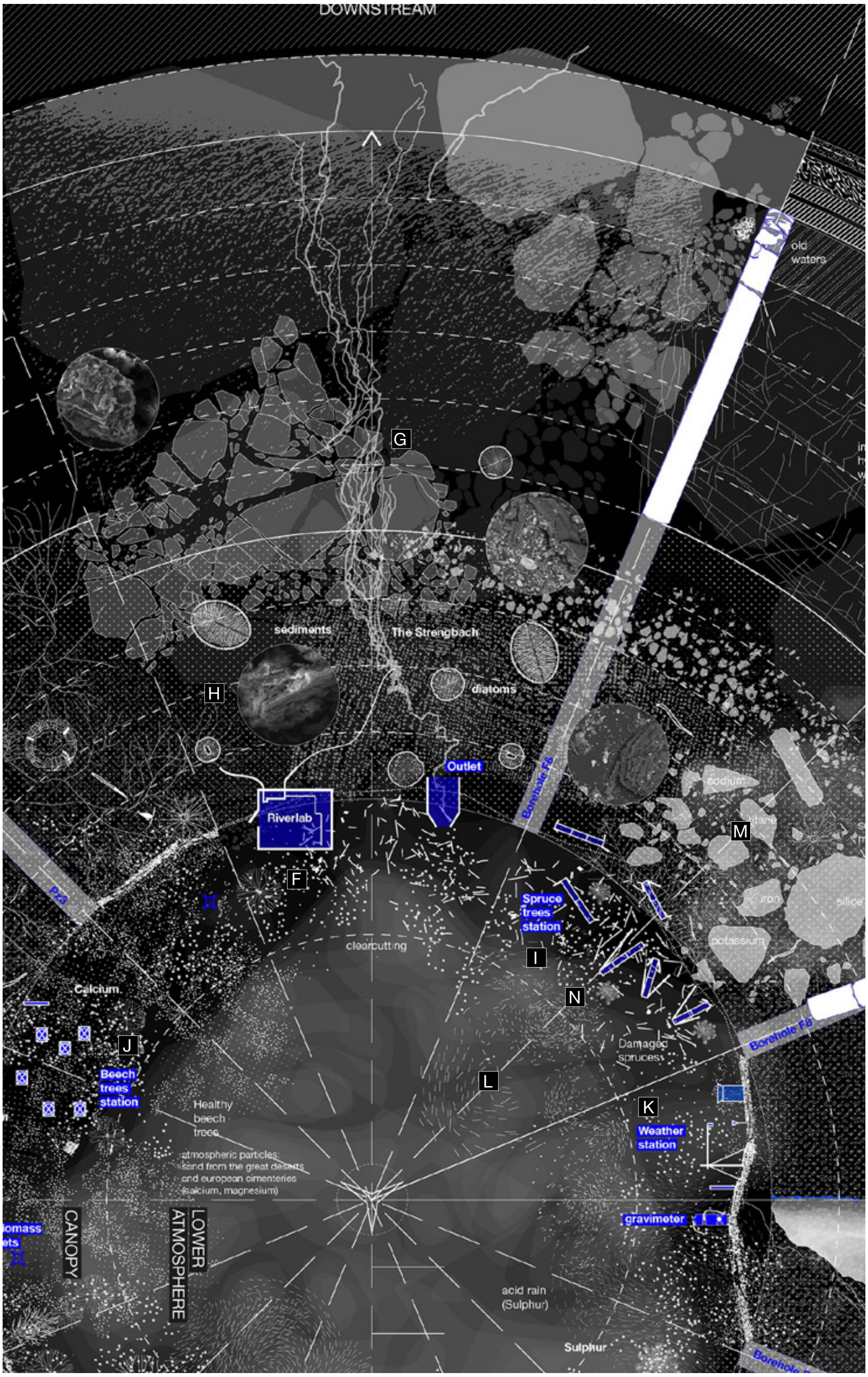


Fig.123. Zooms in the CZO map showing the 'surface' stations

The Riverlab (F), the elemental rivers (G), the components (H); the spruce trees station and its gutters (I), the beech trees station and its gutters (J), the weather station (K); Sulphur in the atmosphere (L), Sulphur in soils (M), Sulphur passing through the canopy (N) the map is an inverted arrow that suggests that the map is oriented towards the ground, by contrast with the satellite cartographic view from nowhere (Fig.124). The extension of the mapping of the territory (that is, the extent to which the cartographer maps the territory) is then subordinated to what can be actually measured with the instruments that comprise the observatory site.

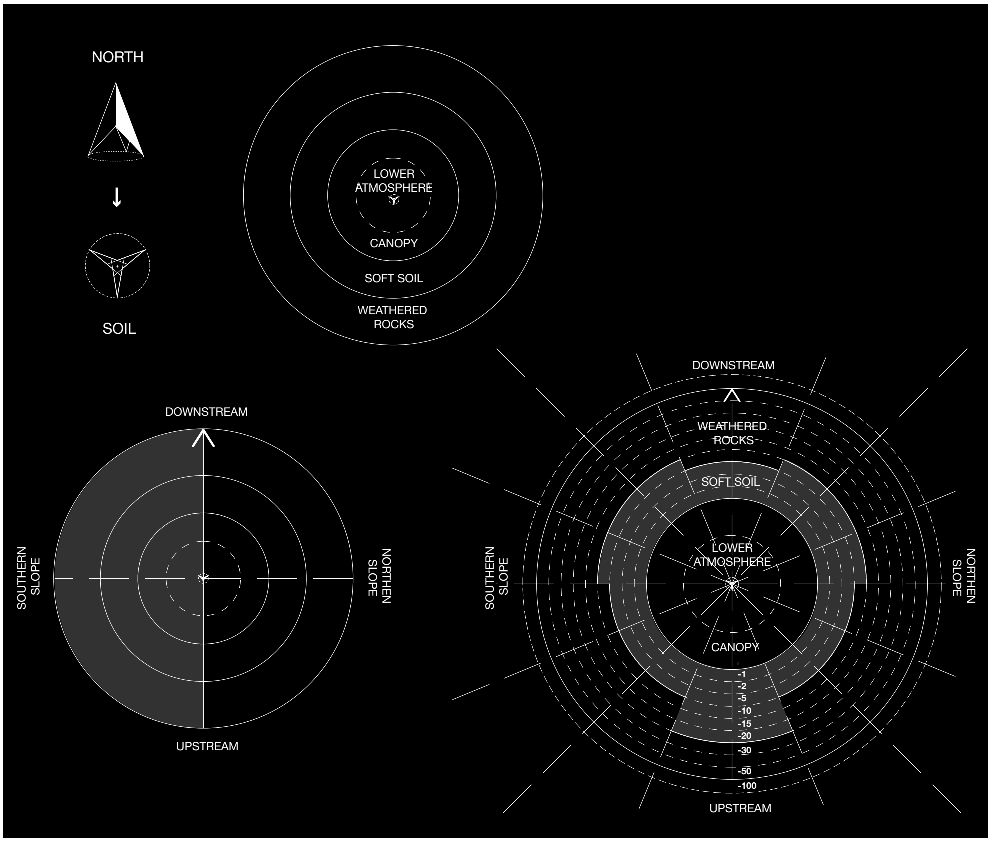


Fig.124. A new map referential

Diagrams of the structure of the map with the change of the frame of reference, the ground, the point of view towards the soil, leads to new coordinates. Drawing by the author.

The measurements and the scales

Not surprisingly, the measurements in the map change according to the instruments of measurement. We argued in the empirical chapters that in order to understand the characteristics, behaviours, and threats to the soil, river, or atmosphere, CZ scientists have little recourse to geographic metrics. Instead they evaluate the chemical content, quantity, time scales, and velocity of trajectories and therefore change the way we understand space and time. On the map, each instrument measures and scales the elements according to their qualities. The map navigates through scales; the microcosm and the macrocosm are intertwined: the bacteria in the soil or the geological granite bedrock are juxtaposed. The circles representing the layers of the CZ are also given a logarithmic measurement and their thickness can vary greatly depending on the location observed and mapped (**Figure 121** is the map of the Strengbach CZO but the exercise could be done for every other observatory, where could be found other instruments and procedures capturing different phenomena).

The background

The circles of the soil, rocks and atmosphere in the projection may vary depending on the site. The projection rules remain the same (with nested circles) but not the spacing from one another. Their adjustment depends on the thickness of rocks layers, or the importance of the atmosphere, depending on each specific observatory. Thus, there is no generic background, just as there is no background that does not change according to the elements that constitute the landscape. Each element transforms the projection and its content, in the same way that entities adjust their environment to their needs as we have seen in the Gaia hypothesis.

The legends

The entities and phenomena made visible by the instruments constitute the legends that are necessary to form the map (since there is no background on which to affix the elements). In this map, the legends are not mere signs signifying something more than themselves. On the contrary, they act fully for themselves **(Fig.125)**.

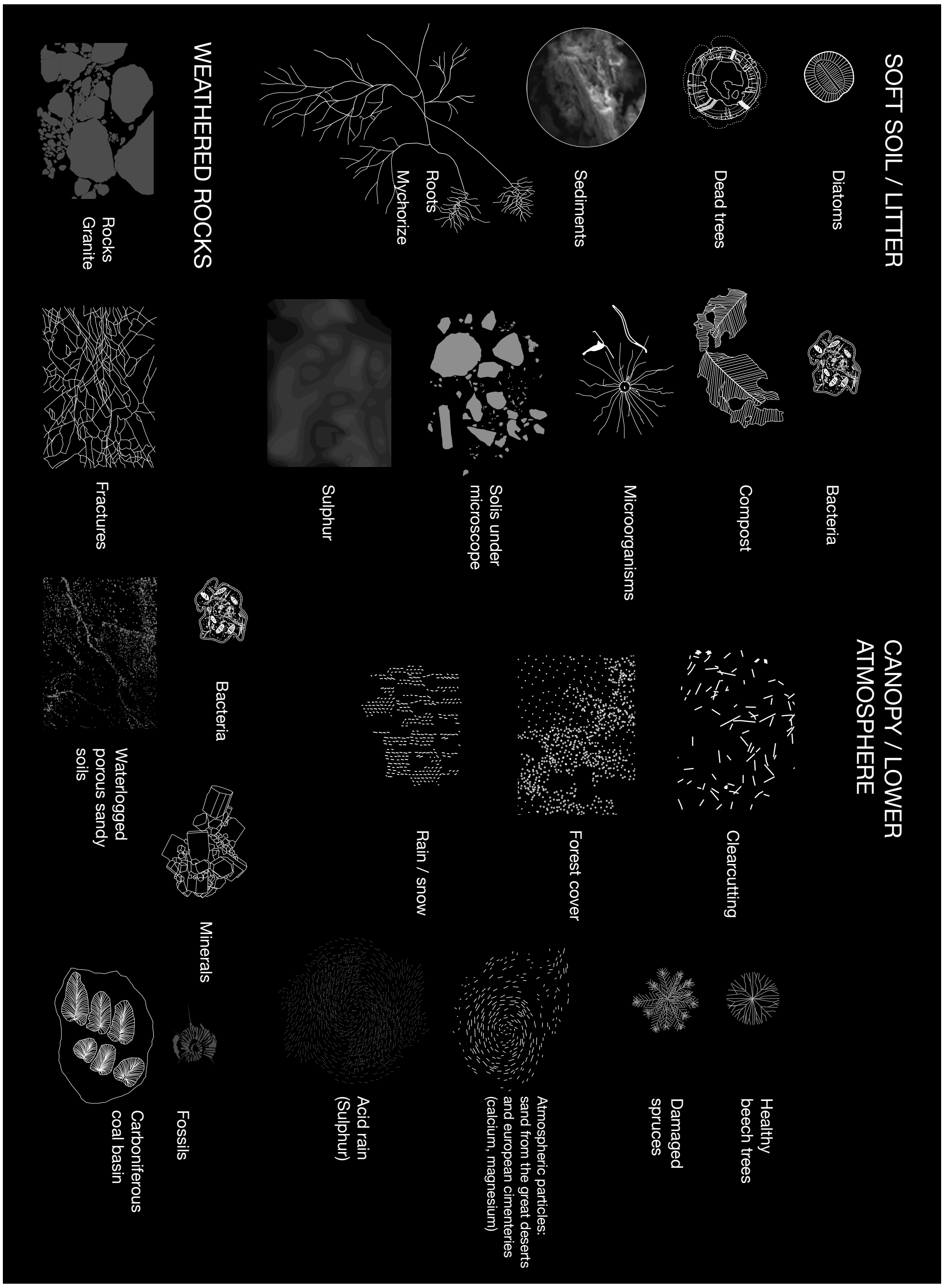


Fig.125. Entities revealed by the map, composing its legend

Legends of materials, elements and entities visible on the map. Drawing by the author.

7.3 Maps from 'within'

Critical Zone science provides sensors that aid our understanding of Gaia by registering phenomena previously hidden or otherwise unavailable to us. The CZ science thus provides new sources for use in drawing maps and changing the cartographic reference frame. Because they are so important, the data collecting instruments are visualised on the map along with the phenomena that allow the scientists greater understanding. The point of showing the instruments is that it is a way to make visible the infrastructure and the practices that are needed to produce the map. The infrastructure for aerial mapping is indeed hidden (satellites are not shown in aerial maps, for example). By contrast the alternative maps developed here bring the scientists of the CZ into the visualisation. The human and non-human relationships are made visible and more articulate by showing the instruments used by the scientists, their methods, and the entities they collect. We thus understand the CZ as an assemblage of humans (as traces or observers), instruments and entities (as particles, organisms or models).

This visualisation can thus be considered a socio-technical map. The map shows the entire apparatus of a CZO. The instruments shown in blue address the argument about the monitored landscape that we developed in the chapter on atmosphere, where we described how devices dispersed in the forest challenge the passive representation of nature. This visualisation is different not because it is an objective map from a distance or a map of a phenomenon, but because it is a map that tells us a story about scientists, their practices and the instruments they use to be able to visualise phenomena and understand the complexity of the environment. It is a map of phenomena to which is added the full array of scientific activity—all the actors who must be mobilised to grasp the phenomena, the cyclical compositions, the displacement of the elements, as well as the flexibility, mobility, cyclicity and fragility of all these elements. It reports on the whole of the work carried out by scientists to apprehend and understand the complexity of the CZ, the techniques and technologies they must put in place so as to be able to apprehend the composite of phenomena, the observatories and laboratories, and the procedures they have to follow. All of this comprises the activity the scientists are engaged in order to understand CZ complexity. The socio-technical map shows this process: the phenomena plus all the work, technologies, institutions and situations that have to be created to account for the complex composition of the Earth. Through the ethnographic work we have traced this process; we have followed the scientists in their observatories and laboratories. And so it is that the map reflects the complexity that we observed in the fieldwork.

The instruments of the scientists collect data from the ground and from the interior of the Earth. Similarly, ethnographic observations provide an inside view of scientists' practices. Thus, what do we gain by being within the "belly of the monster" (Haraway, 1988), of the Earth, where all these cycles and their complexity have been observed? The socio-technical map is in a way done from within this belly of the monster. Situated, entangled, and produced in close proximity to the ethnographic work, the map misses nothing that happens in the time-lapse of the fieldwork. Above all, it avoids the supposedly objective overhanging view, which is in fact a contemplative vision of a passive nature. As we know, cartographies with an anthropocentric view consider nature as silent and figured by man; the point of view of the human subject contemplating the Earth is central. By contrast once more, it seems important to produce another type of visualisation, one that talks on behalf of the phenomena so that we no longer take natural entities for granted. In contemporary perspectival drawings and maps, which are utilizing the same technic as that created in the Renaissance, the world is arranged along alignment lines that all converge toward the single point of view, the human eye. This human subject is itself static and the world perceived in this way is immobile, ready to be arranged and composed from this singular point of view. In the alternative socio-technical map of the CZ, the single eye is replaced by a multitude of instruments that provide different perspectives on the territory. There is no fixed point where everything converges; we have to follow every natural phenomenon, every entity that moves and is followed by the different instruments. Our eyes move across the map and follow the elements one by one. These alternative visualisations promote a more cosmopolitical approach, inviting the users of the maps to follow the movements of each entity, inviting them to discover from the inside the agency of the soil, the river or the atmosphere, to uncover their own ways of scaling, with the result that multiple scales intertwine in the map. The map thus does not reduce the workings of the world to a *single* world but captures the existence of a *pluriverse*.

This alternative way of visualising the CZ has been discussed with CZ's scientific community[107]. Their reactions were varied. Some felt that their work was better represented: "at last, the surface layers I work on are given importance and the deeper layers are pushed to the periphery"; others felt better oriented: "we know better where we are"; or reassured: "we are no longer floating in an infinite space like with the globe". Others, however, felt confined: "but then we are enclosed in the CZ", a feeling that was quickly mitigated by the possibility of visualising the infinite movement of the cycles that we will describe in the next part of this chapter. Thus, for the first group the important point was to be able to define a new framework. For the second group the most important aspect was not to lose the dynamics, the 'cosmo-tectonic maelstrom', i.e. the time scales and speed of the cycles, and especially the disruptions introduced by human activities. The work on the alternative map was pushed further by joining with the scientists to visualise the cycles they trace in their research. This work extends the ethnographic observations and goes further by creating a collaboration with the scientists, even helping them to formulate new scientific questions. It is an extension of the cosmopolitical approach towards an ecology of practices, as Stengers suggests.

In the chapters on soil, river and atmosphere, we have demonstrated the importance of cycles in understanding the CZ. Thanks to these empirical chapters, we can assess that habitability in the Anthropocene is disturbed, and that this disturbance is visible in the cycles that scientists trace through the monitoring of territories. The cycles of a territory are therefore a good reference for defining habitability criteria, i.e. determining what the limits of habitability are in a specific place. For example, how much CO_2 or nitrogen in the atmosphere is acceptable? Or below what level of nutrients

107 In an article: Arènes et al., 2018
In a book: Aït-Touati, Arènes and Grégoire, 2019,
In an exhibition: ZKM museum in Karlsruhe, Germany, and on the website of the virtual exhibition,
In other lectures and workshops.

(calcium, magnesium) does vegetation in a city no longer grow? In addition to the above, it is important to recognise these cycles because first, they introduce a terrestrial dimension to architecture, so as to understand the impact of architecture on the scale of the Earth; second, they allow us to focus not only on static materials but also on how they move and from which territory to another; and thirdly, they allow us to include the notion of time in design, which is often neglected in favour of space. For example, the Anthropocene has accelerated soil erosion rates so that regeneration of soil production is impossible, as we have seen in the chapter on soil. It is therefore important to recognise the speed of the processes so as to understand what soil will remain for the next round of regeneration. We propose to use the map projection presented at previous points in this chapter to represent these cycles with slight adjustments that we will describe below.

Discussions with CZ scientists led to suggestions other aspects to be taken into account in the map, such as processes, speed, important elements, i.e. all the geochemical information needed to understand the cycles. This work with the scientists allowed for a systemization of the visuals. Consider water movement for example. We saw in the chapter on river what scientists are tracking across the CZ through the sampling and water chemistry analysis that provides information about how the Earth is reacting to environmental disturbances. The bio- and hydro-movements set the elements in motion, in cycles, and so terraform the landscapes. Cycles in the CZ can move from the surface to the depths or from the depths to the surface, losing or gaining speed with each transfer, and also losing or gaining quantities of chemical elements, engaging different processes and generating different changes in the behaviour of the environment. A cycle is generated because of the different processes that occur in the layers of the CZ, i.e. when elements pass through different types of rocks, or when they pass into the atmosphere or into the depths. The direction of cycling, its speed and quantity are therefore important.

To account for these processes, the map sets up a coding of lines to visualise the cycles of an observatory **(Fig.126)**. In this map, the trajectory of a cycle is visualised in two directions: centrifugal, from the centre to the periphery, i.e. from the atmosphere to the rocks; or centripetal, from

Fig.126. Diagram of the principles of a map of cycles
The projection of the socio-technical map used to depict the cycles in the work with the scientists. Drawing by the author.

the periphery to the centre, i.e. from the rocks to the atmosphere **(Fig.127)**. With this grammar, a cycle can be followed: where it comes from, where it goes and how it comes back. Each process forms a line, an arc of the cycle on the map. Most importantly, the speed at which a process is taking place is visualised. To do this, angles are given to each arc that makes up the cycle. If the angle of the arc is flat, it means that the process takes place over a long period of time. On the contrary, if the angle is acute, the process takes place over a shorter period of time. And if the line is almost vertical, it means that the process is accelerating **(Fig.128)**. This code helps to understand how each process depends on the energy sources that drive the cycles **(Fig.129)**. If one of the cycles is disturbed, this can also be seen with this system, as we look an example of the sulphur cycle.

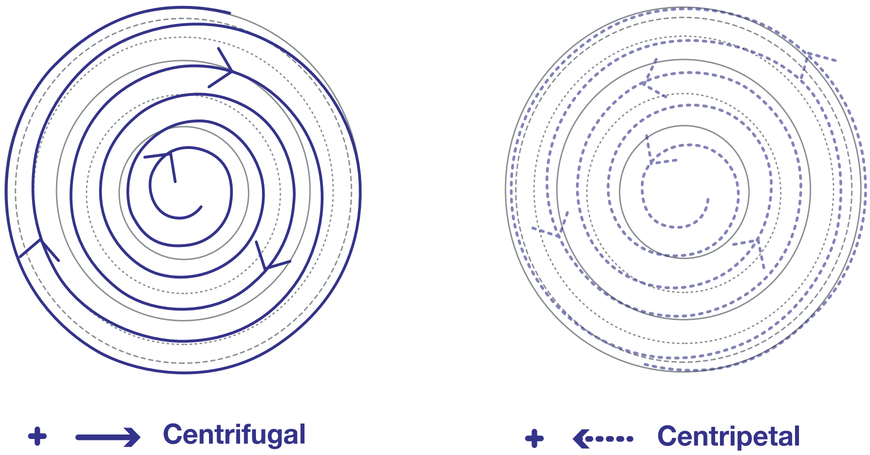
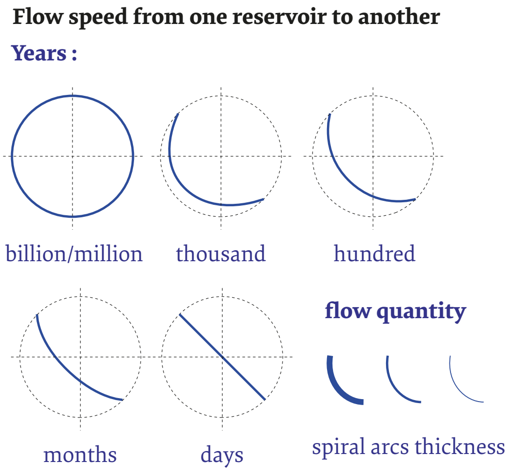
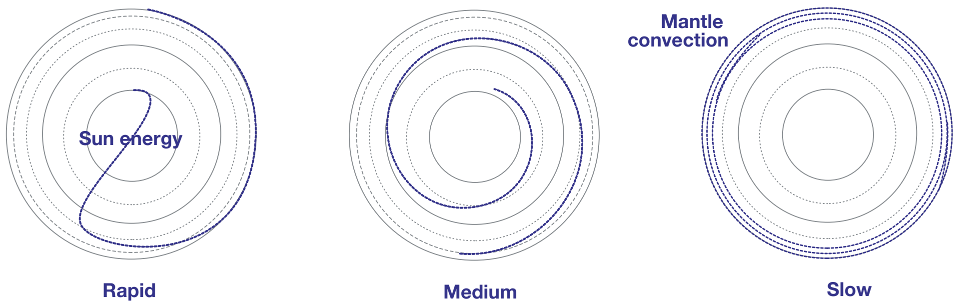


Fig.127. The cycles ways: the spirals grammar
The cycles are represented by spirals originating from the atmosphere or from deep rocks: they move in one direction or the other, from the surface downwards or the other way around. The first movement is centrifugal (the elements are dispersed in the rocks and leave the observatory boundaries) and the second is centripetal (the elements rising to the surface concentrate in the atmosphere where they are captured by soils and biomass). Drawings by the author.

Fig.128. The cycles speed: the spirals angles
The cycles move at different speeds. Thus, we give a speed to the angle of the spiral, ranging from flat (slower movement, almost always influenced by the mantle cycle) to rapid (faster movement, almost always related to the components that rotate in the atmosphere). Drawings by the author.





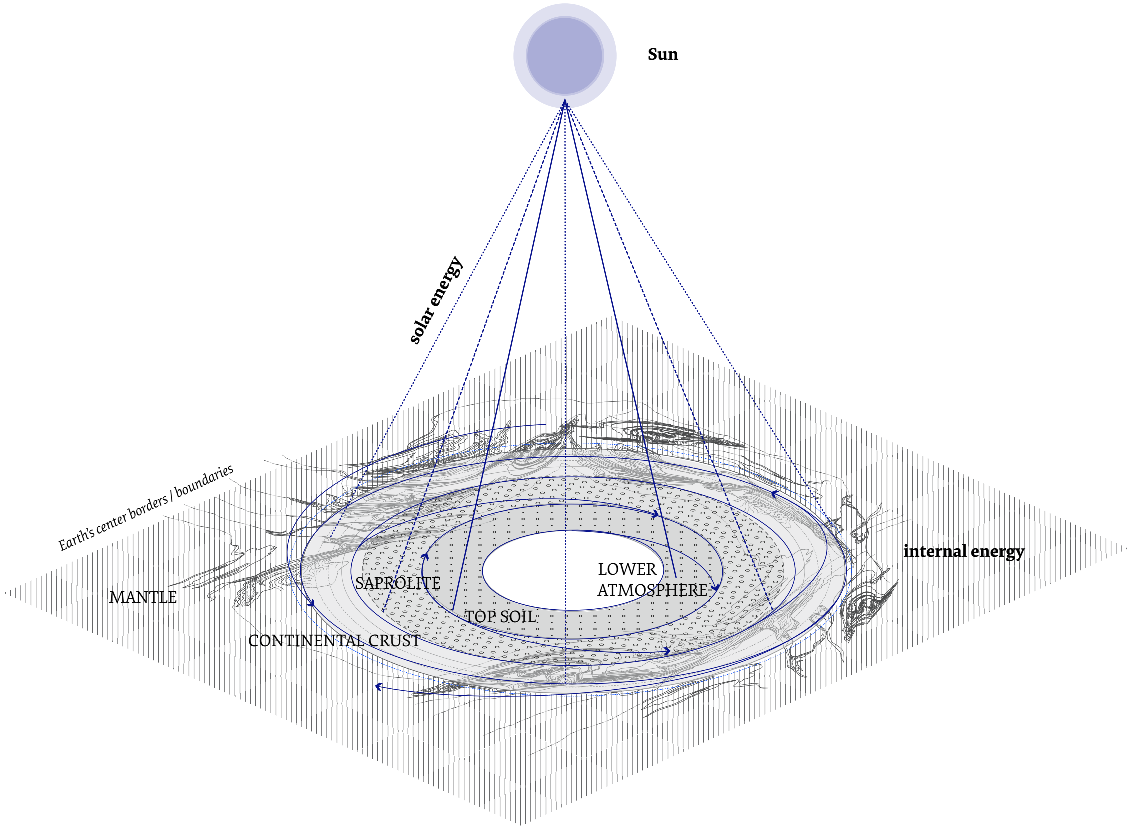


Fig.129. The energic maelstrom
In this diagram, the projection has been rotated and flattened into an axonometric perspective to show the two sources of energy that drive the cycles in the Critical Zone: the sun from above and the deep Earth from below. Drawing by the author.

To render this example, we mapped the cycle of sulphur (the element that causes acid rain) at the Strengbach CZO **(Fig.130)** with Marie-Claire Pierret. As we have seen in the chapter on atmosphere, scientists have been tracing the effects of sulphur on the Vosges forest by collecting rainwater at different locations every fortnight for the past 30 years: directly from the rain, through gutters under trees, and from reservoirs in the ground. All these samples are then brought back to the laboratory for analysis. The analyses are then collated to produce graphs of sulphur chronicles. These graphs allow scientists to see how sulphur has decreased over the past 30 years, but also how it is still present in the soil. The chronicles provide an overview, but do not provide a true understanding of the trajectory of this cycle and its impact on the land. To remedy this shortcoming, the map of the sulphur

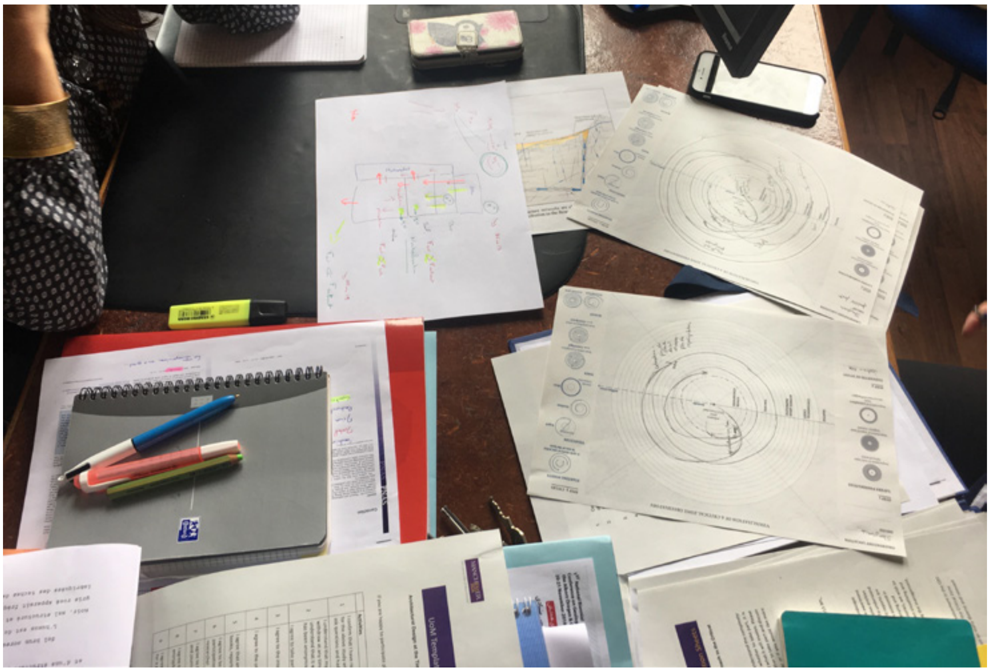


Fig.130. Working on the sulphur cycles

The work session with Marie-Claire Pierret at her office (OHGE Strasbourg) on the visualisation of the Sulphur cycle in the Strengbach CZO. Photography by the author.

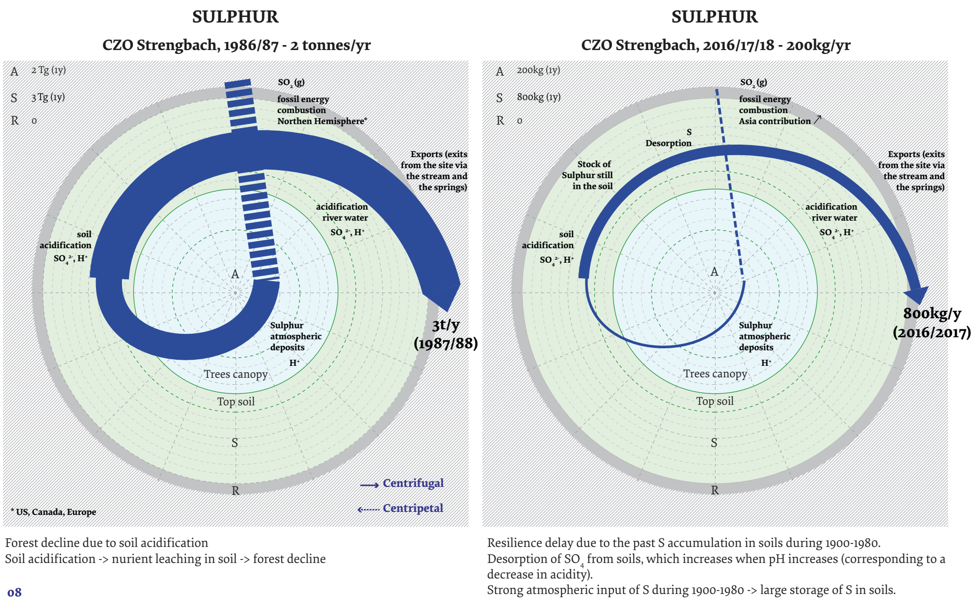


Fig.131. The Sulphur cycle at the Strengbach

Alternative visualisation of the terrestrial cycle of Sulphur at the scale of the Strengbach CZO, for the year 1986/87 and then 2016-2018, showing the impact of the Sulphur cycle on a local observatory. Drawing for the catalog of the ZKM exhibition, by the author with the data from Marie-Claire Pierret, geochemist at OHGE Strasbourg.

cycle in the Vosges forest describes how sulphur enters and leaves the observatory as well as describing its trajectory: how much sulphur is deposited on the forest, where does it go next (into which soil compartments?), how rapidly does it pass through the cycle, and what is the impact of the element sulphur that causes acid rain and comes from distant factories. The map uses the sign grammar, or code, described above to account for the movement of the sulphur cycle **(Fig.131)**. The map shows a line, the path of the sulphur through the layers of the CZ, from the atmosphere to the rocks or from the rocks to the atmosphere. It indicates the amount and speed of the sulphur element relative to the organising cycles. If the element spends a lot of time in one of the layers, then the angle of the spiral is curved, on the contrary, if the sulphur is moving more quickly, then the angle is acute. In this case the map effectively visualises the result of excessive mining and fossil fuel consumption, a combustion process that produces more sulphur than the system can absorb. In the chapter on atmosphere, we followed the scientists into the Vosges Forest and observed how the long-term monitoring by this observatory with all its instruments allowed the scientists to trace and to compare the amount of sulphur in the past and today. The two maps depicting this cycle 30 years apart reflect this tracing process and show the evolution of the sulphur cycle from peak emissions to today's gradual but not complete decline. This visualisation therefore shows the human disturbance on the biogeochemical cycles and their long-lasting effect. This is in fact the human signature in the Anthropocene. The sulphur cycle at terrestrial scale has also been mapped with the help of Jérôme Gaillardet **(Fig.132&133)**.

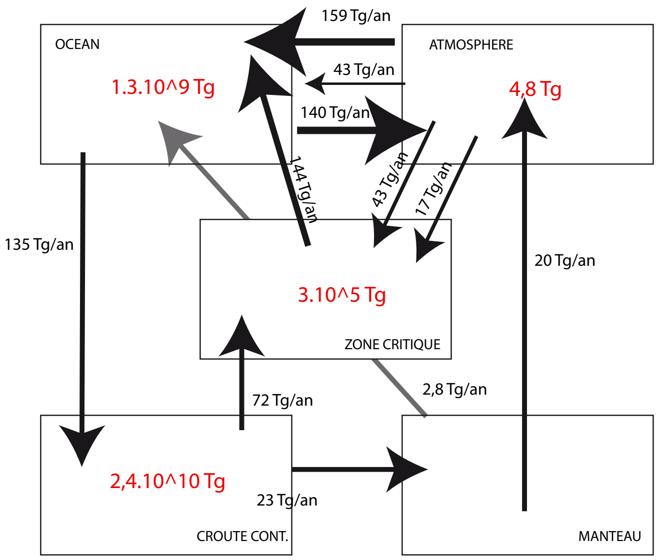


Fig.132. Conventional representation of cycle with boxes

Diagram type 'box and flux 'of the Sulphur cycle at terrestrial scale with the Critical Zone in the centre, by Jérôme Gaillardet during our work to create new visualisations of cycles for the Critical Zone.

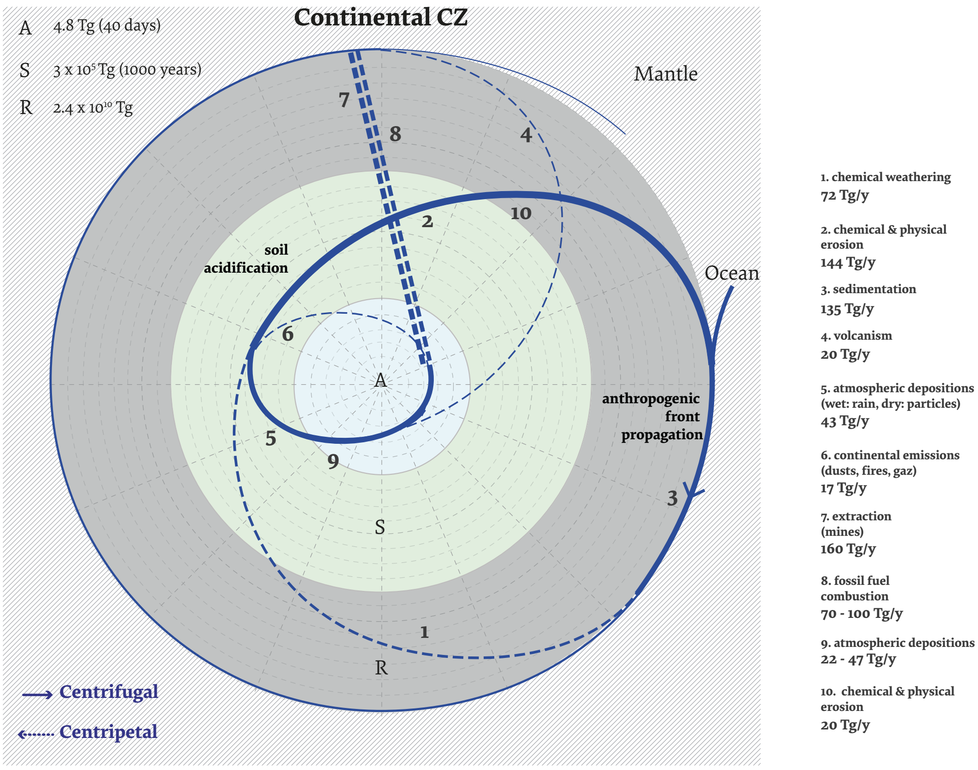


Fig.133. The Sulphur terrestrial cycle

Map of the Sulphur cycle at terrestrial scale using the projection described above. Complementary to this work on a particular CZO, we draw the terrestrial cycle of Sulphur, that is the whole cycle of Sulphur throughout the Earth (Figures 119 and 120). This drawing shows the difference with a cycle on a local site, which doesn't loop and the cycle at the global cycle, which loops – the global is a boundary condition. Drawing by the author.

Another concrete example is the map of the carbon cycle at Earth scale (Fig.134). As we have seen in the chapter on atmosphere, the carbon cycle is one of the most important cycles for life on Earth, and yet there are still blind spots regarding its tracing at depth. The map of the carbon cycle is therefore an important attempt to trace the carbon through the layers of the CZ, especially at depth. Based on the findings of the empirical chapter, each time the element is transformed the line bifurcates and takes another angle while spiralling. If the transformation of carbon occurs over a long period of time, as in subduction (process 8), the angle of the bifurcation is curved. On the contrary, when the transformation occurs in a short period of time, in day in the case of the respiration (process 2), then the angle is acute. The line thus rises regularly, balances in both directions (deep and at the surface) and loops—except at one stage. When the carbon stored in the deep strata is extracted and brought to the surface very quickly by human industries (process 7), the line cuts the 'natural' spiral and the elements are not allowed to be slowly transformed and digested by earth processes. The cutting line, the sharp extraction, shortens distances in space and time and does not loop. It remains suspended in the atmosphere. The map therefore shows that the human signature is a shortcut through the earth layers, disturbing the carbon cycle. As we know, human industry is an accelerator of CO_2 circulation. In this map, the arguments drawn from the empirical chapters are visualised: humans appear as a trace, a disturbance of the biogeochemical signal at the time of the Anthropocene.

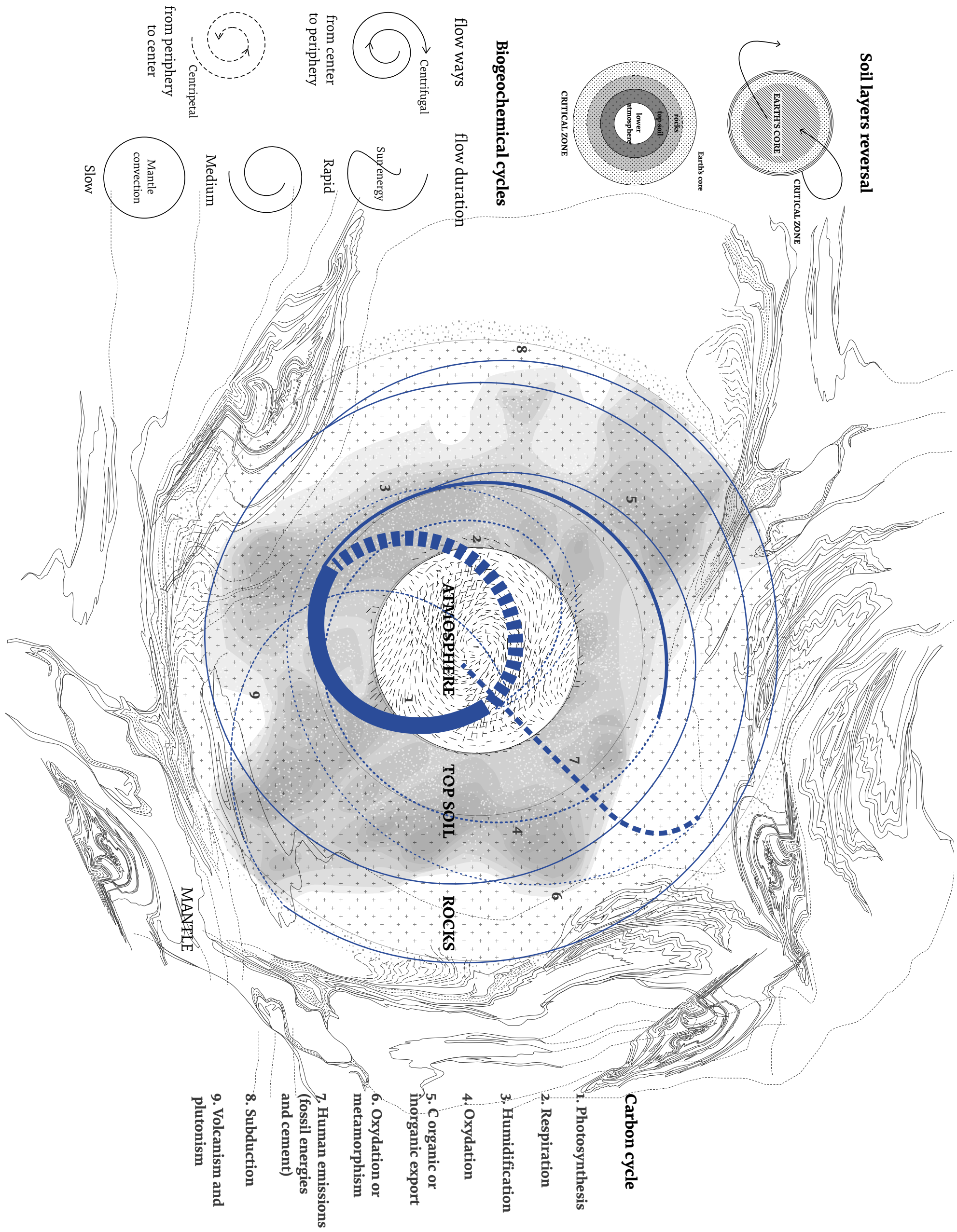
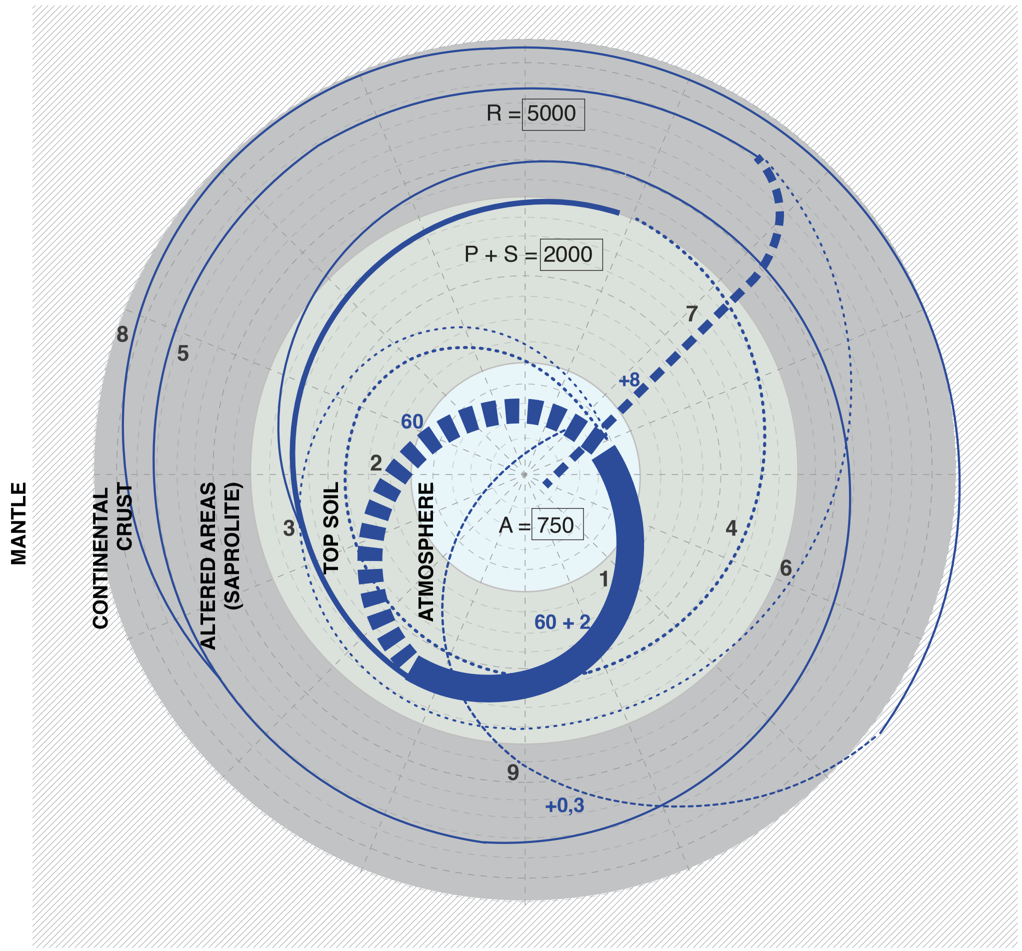


Fig.134. Gaiagraphy of the carbon cycle

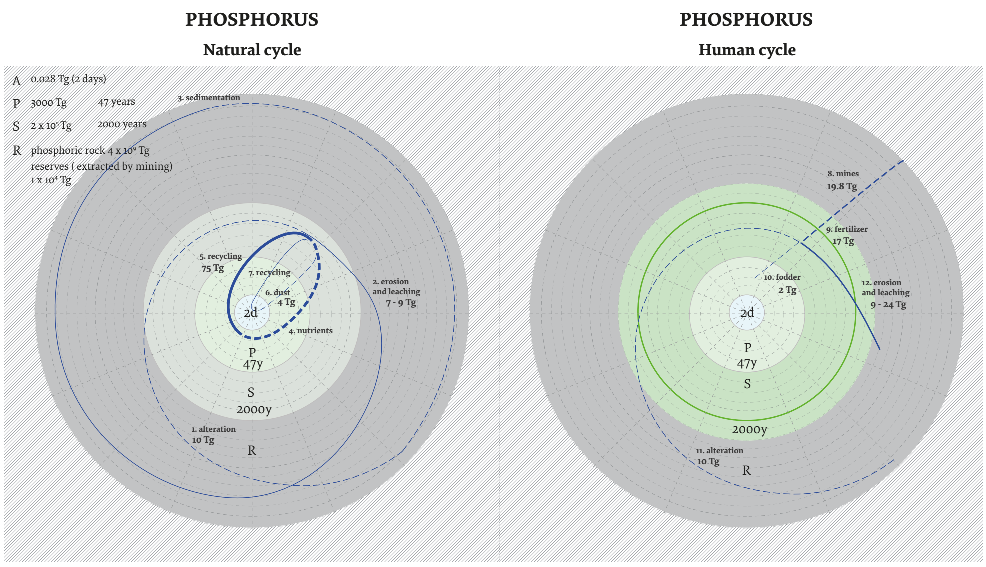
Two versions of the map of the Carbon cycle at terrestrial scale. The terrestrial carbon cycle in the Critical Zone, carried out with the help of IPGP (Institut de Physique du Globe in Paris) scientists. The figures correspond to the amount of carbon in each reservoir in gigatonnes (Gt) for the atmosphere, soil, and rocks. The spirals describe the trajectories of the carbon in each layer and their thickness the amount of carbon lost or gained during the transfer. Drawing by the author.



1. photosynthesis
2. respiration
3. humidification
4. oxydation
5. C organic or inorganic export
6. oxydation or metamorphism
7. human emissions (fossil energies and cement)
8. subduction
9. volcanism and plutonism

Some important cycles are disturbed by human activity:

Phosphorus: minerals are extracted from rocks to fertilise soils. However, the stock is limited and some scientists warn that there will be none left in less than 50 years. In the meantime, as it is overused in soils, it is leached out by water and escapes into rivers, causing eutrophication in aquatic environments. In future work, we could also follow calcium and magnesium which are important nutrients for the soil and plants, and which are decreasing rapidly



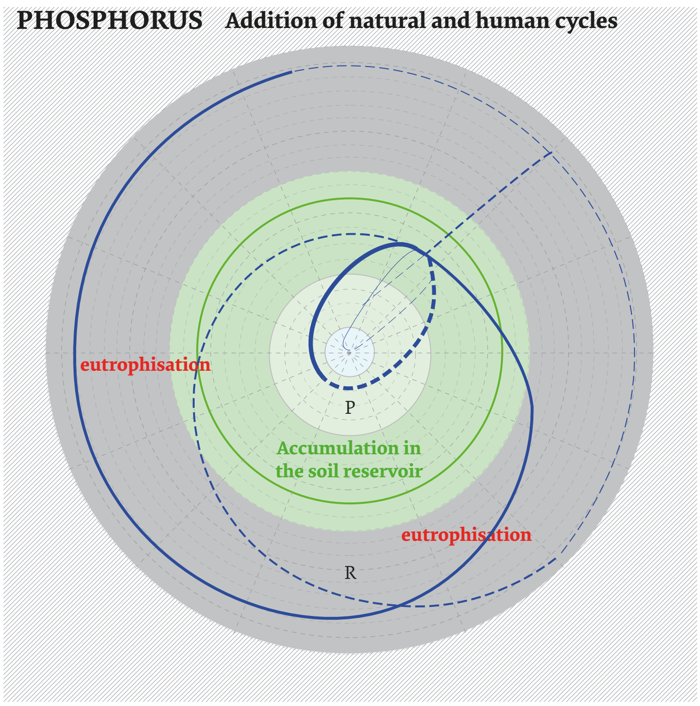
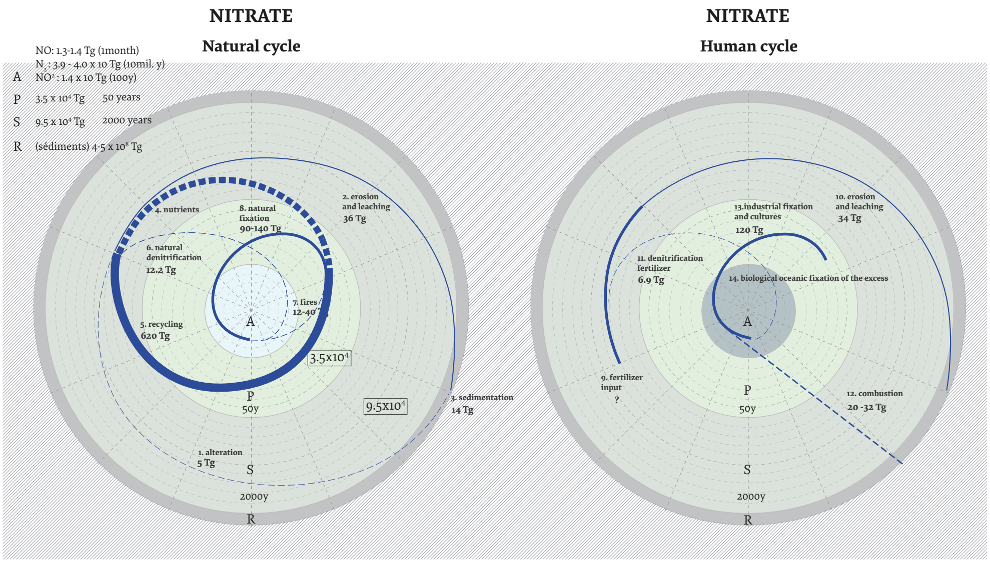


Fig.135. The phosphorus cycle

Map of the Phosphorus cycle at terrestrial scale using the projection described above. The different processes of the cycles are decomposed in order to see the impact of human activities on the cycle. Drawing by the author.



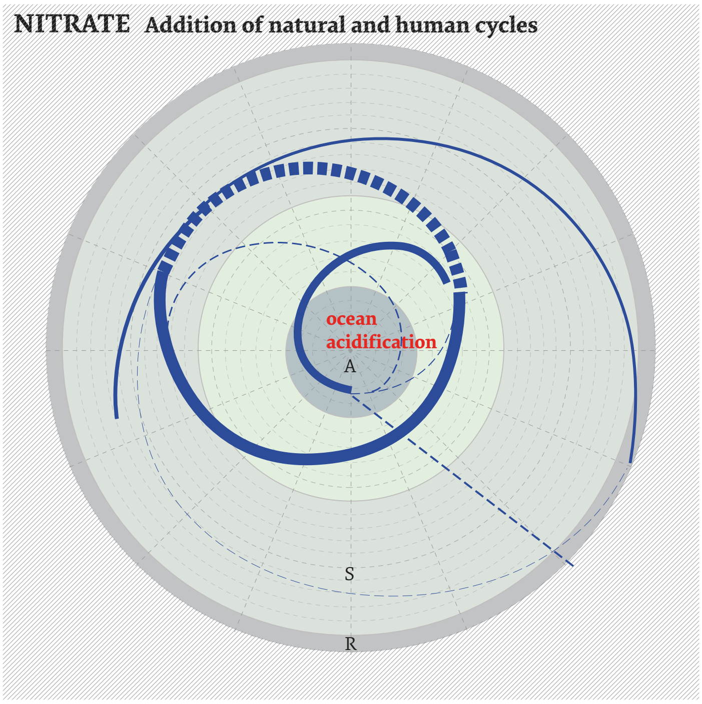


Fig.136. The Nitrate cycle

Map of the Nitrate cycle at terrestrial scale. Humans are injecting more nitrate into the system, either in solid form (a cycle that did not exist before) or in gaseous form (e.g. cars), causing acidification throughout the CZ. Drawing by the author.

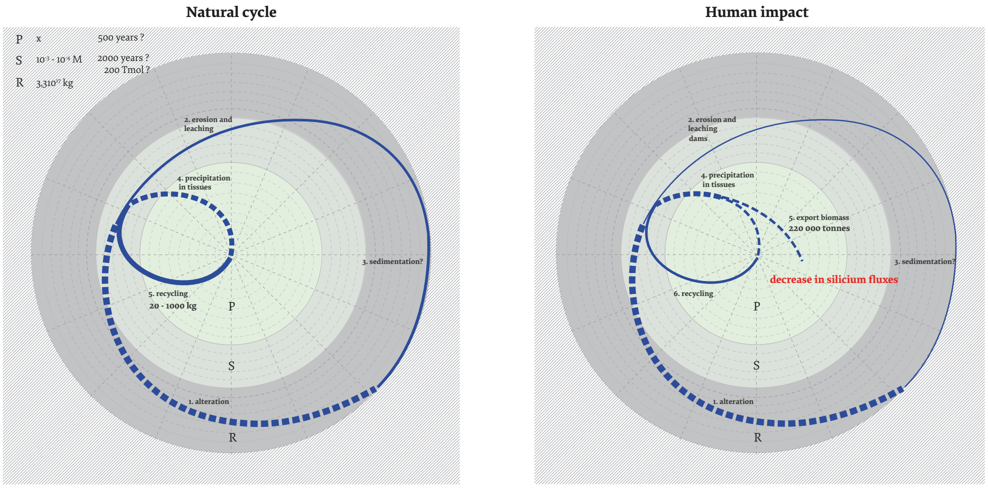


Fig.137. The Silicium cycle

Humans export biomass that contained Silicium, which weakens the whole cycle and reduces biological recycling

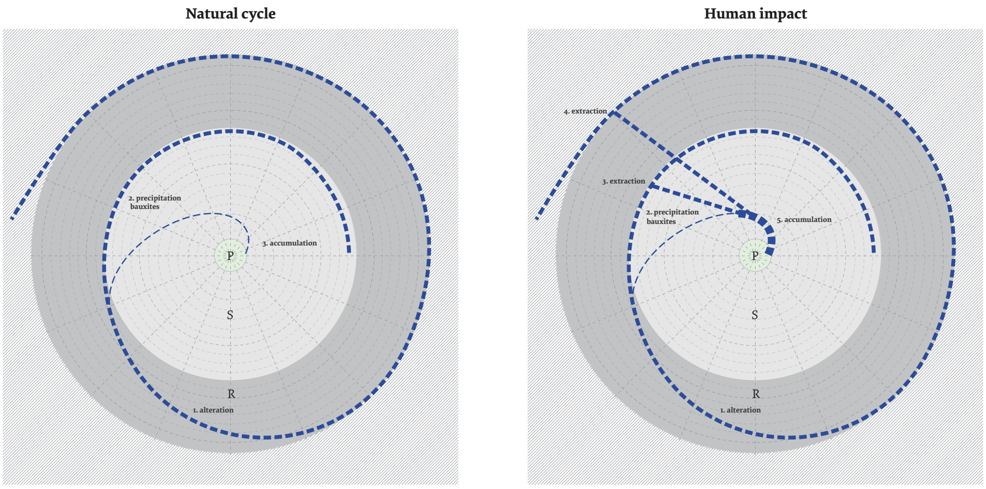


Fig.138. The Aluminium cycle

Aluminium is added to the CZ by extraction from the depths, generating pollution and health problems.

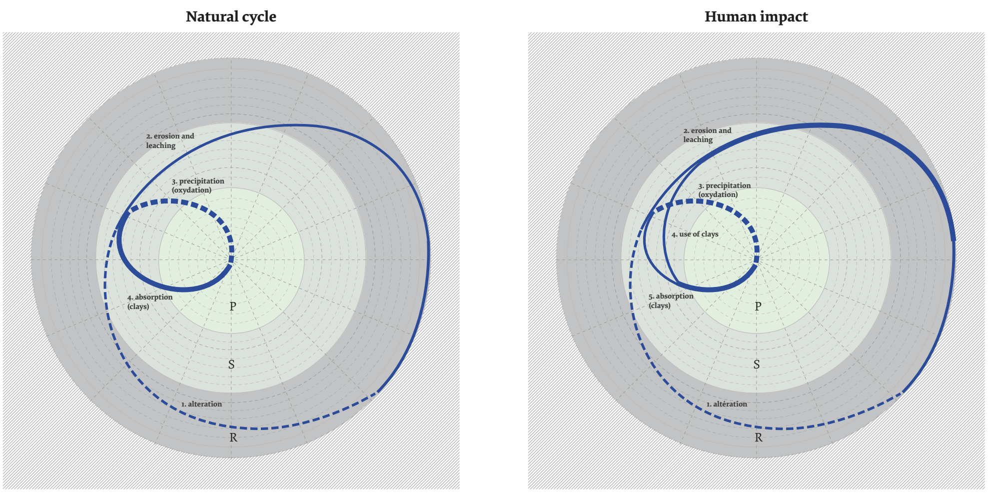


Fig.139. The Iron cycle

The addition of iron to the CZ increases its precipitation which contributes to the destabilisation of soil structures

7.4 Conclusion: a gaia-graphy of the Critical Zones

The Earth, Gaia, is understood as feedback loops by the CZ scientists, not only in cybernetic terms but also as spatial envelopes and temporal historical events that continue into the present. The instruments in the field and the procedures of the scientists allow us to feel, experience and understand these cycles. In the CZ not everything is known in a global, holistic or panoramic way. On the contrary, the CZ highlights certain connections that allow the scientists to gradually grasp the loops in which humans are inserted. The territory is made up of these loops: we are dependent on them and we maintain them at the same time. Mapping the CZ with the cycles enables us to visualise these loops.

In the previous chapters, we have seen that cycles are linked to model making. With the maps on cycles we are no longer in the field with the instruments; now, after the collection of field data, following the completion of the laboratory analyses and the writing of articles, we are at the final stage of the scientific procedures, the model-making stage. We have produced maps at a more abstract level than those of an observatory (like the one representing the Strengbach CZO). Indeed, these maps operate at a conceptual level, aimed at displaying how the habitability of the CZ is represented on a territorial map (i.e., a map located somewhere in particular). Considering how the Gaia hypothesis deals with this notion of habitability, it can be said that these maps, which give an account of the cycles that allow for the Earth's being habitable, are drawn up according to what we might call, following Bruno Latour, a gaia-graphic approach. These maps do not represent objects but the biogeochemical dynamics in which the territory is engaged, good or bad. They therefore do not assess the location of objects by measuring the distances between them, but rather they display the degree of crisis of a territory facing environmental changes by tracing and measuring the quantity and course of chemical elements that are either pollutants or nutrients. With these alternative maps we ask: how can we account for habitability in the Anthropocene? And how can these maps be used in territorial planning? This type of geochemical map describes the crisis of habitability of a particular territory: how it is disturbed, but also perhaps how it could be restored by changing this or that practice, by modifying this or that parameter so that the cycle maintains a habitable territory. Equipped with these maps, architects could evaluate each cycle and propose in a territorial planning project to work on a particularly problematic cycle and doing so by evaluating the dynamics, the evolution, the possible changes, the mutant states. In this way their expertise (combined and in collaboration with scientists) would have a significant impact on the territorial policies.

These maps respond to the challenges of the Anthropocene. They include time and different time scales, from the geological scale (long processes) to the human scale (rapid resource extraction), bridging the gap between understanding the Earth and understanding human activities, between incommensurable time scales (i.e., lack of common measures) that collide in the time of the Anthropocene. In this map, the line is no longer a separation between two entities, but on the contrary connects them in a common trajectory and generates dynamic cycles observed at macro and micro scales by scientists. Scientists trace the manifestation of life through these movements of lines. Scientists trace life but not as a 'form', as an organism with a form. Rather they trace life as its *signature* on territories whose forms depend on these 'signatures of life'. The cycle lines on the map are these signatures. This is an important shift in the understanding of nature, from a naturalistic and anthropocentric view in which natural entities have a shape, a form, to a dynamic view in which entities are distributed and in motion.

These maps are drawn from within the experience of the CZ scientists, their instruments, practices, and procedure. Thus, these maps are drawings from *within* 'the cycles', the Earth movements. Making maps from within involves negotiating with many more entities than in the anthropocentric view in which man is the main subject. We have adopted a cosmopolitical perspective and design. This cosmopolitical view means relying on new materials, actors, scientists, and entities. It means finding new spaces, opening up new time scales. It opens up the possibility of greater resiliency because we appreciate the Earth's greater connectedness. And we see repopulated maps where before the natural world was hopelessly empty and silent. All of this has a clear purpose: preparing us for climate change and the challenges to architecture, landscape design, urban and territorial planning at the time of the Anthropocene.

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8 Conclusion: a gaia-graphy of the Critical Zones

8.1 Summary

The New Climatic Regime is the result of major disturbances to the Earth system caused by human overactivity. Devastating events such as floods, fires out of control, food and water shortages, the disappearance of soils or latent crises such as chemical pollution, all prompt the need to understand such phenomena, their cycles, the Earth's reactions, and the composition of the environment. Indeed, the Earth's habitability is threatened by human ways of living, constructing, and managing territories. In their practice, architects are confronted with injunctions to restore ruined lands as quickly as possible using renaturation and regeneration techniques' however, these are sometimes insufficient greenwashing solutions or focus on the 'economisation' of natural processes. The aim of this dissertation is to address practical problems of understanding the Earth and the elements that architects are dealing with: soil depletion, pollution, waterways and such. We have learned that landscapes cannot be understood as objects when we see them react violently to human activities (as Gaia's revenge reminds us). We are instead led towards the need for a different understanding of territories and landscapes in order more fully to understand their complexity, to understand all the issues that are entangled with a river, the climate or a forest.

What could be done to gain this understanding? To answer this question this study investigated the complexity of territories from within, that is, as seen through the practices of the Critical Zone (CZ) scientists who are the ones who observe the Earth's reactions carefully and in depth. More than objects, they look at landscapes as phenomena, cycles, and varied and dynamic compositions of elements. To carry out my investigation I followed these scientists at work in several of the most critical (and damaged) zones of the Earth. I sought to understand the complexities of territories and phenomena in five of their CZ observatories over the course of a year, spending weeks and days in the natural sites and their associated labs, especially at the IPGP in Paris. I met and talked to more than 50 scientists and conducted interviews with a dozen of them.

This ethnographic journey into the CZs constituted the content of the empirical chapters which focused on three particular elements—soil, river, and atmosphere—because they are the most often studied by CZ scientists. An empirical chapter was devoted to each of these three, each reporting the findings of an ethnographic approach that was common to all. The ethnographic journey explored how the natural entities become different according to the Critical Zone lens: through the scientists' instruments ('observing'), the entities of nature are decomposed ('decomposing'), allowing the scientists to trace them differently ('tracing') and thereby to propose a new reading of the territories ('connecting'). The descriptions of these entities of landscape and the findings stemming from these descriptions allowed me to grasp the composite nature of landscapes and to understand territories in a different way. Once the empirical chapters were in place the chapter on mapping could serve as a bridge connecting the empirics and this general conclusion. The bridging chapter, 'Mapping the Critical Zone' focused on visualisation, on how understanding of nature can be translated visually and thus be effective for architects who use graphic means to think and act (in design). The visualisations proposed in that chapter are different from the cartographic tools for top-down visualisations of the earth that rely on satellites. Instead, the visualisations based on the CZ findings are made from within: they are a composite of CZ knowledge, the practices of the scientists, and their array of instruments. The visualisations aid in the development of new mapping paradigms, methodology and models (structures) of the world as seen through the CZ. They bring a different awareness as they describe the Earth from within and from within the crisis of habitability, shifting towards a cosmopolitical visualisation of the Earth. Therefore, it may give architects a better kind of equipment for more fully understanding the gravity of environmental issues, the provision of tools for mappings/cartographic representations that can better deal with the Anthropocene, the New Climatic Regime.

To draw the thesis to an end, this concluding chapter is split into three parts. The section on 'a new understanding of nature' is a summary of the key findings from the three empirical chapters and the chapter on visualisations. The section on 'interdisciplinary research' recounts the key arguments and contributions regarding the knowledge gaps identified in the Literature Review. The final section expands further prospects for work.

8.2 A new understanding of nature

In each empirical chapter we have observed recurrent practices which shift traditional understanding of what is a soil, a river and the atmosphere. This new understanding is first gained by a network of instruments that the scientists deploy in an observatory of the landscape. These instruments bring a different understanding of natural territories. Indeed, without the work of the CZ scientists, many phenomena in natural territories remain invisible. Therefore, the instruments and scientific research must be adapted to address a certain myopia, the short sighting of the natural entities whether because of obscurity (deep soil) or their microscopic condition (water or atmospheric particles). Moreover, with the use of the CZ instruments natural territories become environmental sentinels (with sensor ability), ambassadors (for example the Riverlab is a micro architecture, a small lab in the field that welcomes scientists and inhabitants) or monitored landscapes (filled with multiple devices across the forest). This changes the traditional status of these sites from "natural" to composite. Finally, a natural territory instituted as an observatory by the scientists becomes a special place where concerns gather as several scientists address their different scientific research questions linked to environmental issues. Therefore, the instruments, protocols and the practices put in place by the scientists expand senses, knowledge, expertise, and issues on natural territories. The chapter on visualisations featured the socio-technical maps drawn from the CZ findings generated by new research methods. The new maps make explicit the expansion of what is viewable by representing these instruments, scientific procedures, and apparatuses as scientists seek to understand differently what a soil, a river or the atmosphere is, thus enabling the mapping of a completely different territory.

This network of instruments shapes a new understanding of nature by decomposing landscapes, bringing many more entities into visibility. The CZ sciences expand the quantities and qualities of the entities to consider and so the landscape is no longer a pre-unified environment with taken for granted entities. Depending on how we look at the landscape, it could be "exploded", decomposed, disassembled, dissolved; that is what the scientists are doing in their practices, in their back-and-forth movement between the field and the laboratories. Because the scientists refer to the field, their practice differs from traditional scientific practices which are based on 'extraction'. Therefore, the understanding of the landscape that the scientists now bring is reminiscent of a pluriverse. There are many flows of a river, elemental rivers (river of calcium, river of phosphate, river of nitrate). The soil is porous and no longer understood as a unified block, a surface; it is instead seen as an entity in motion, with holes, depths, cracks, fractures, particles. The tree appears as an "holobiont", composed by other entities (mushrooms, fungi). The notion of pluriverse (James, 1909) avoids seeing the world through a single lens, a single mode of existence. Instead the notion argues that there are many modes of existence. Moreover, the CZ enables us not to focus on the form of the entity (for instance the river as an object delimited by two lines) but rather on the various elements that compose it. Following what we have learned from the empirics, the visualisations designed in the chapter 'Mapping the Critical Zone' do not represent the soil, or the river in pre-conceived ways (surface, lines), but instead they aim to expand the number of elements and entities, showing their qualities, behaviours, times, and spaces. At the same time, the mapping procedure creates a composition by ordering and arranging these decomposed elements into a diagrammatic scheme acting on behalf of the CZ cosmology.

This composition of nature is carefully traced by the scientists. Each entity (the soil, the river, the atmosphere) and what composes it at granular scales is followed through various spaces, scales, and timelines, some of which we didn't take into consideration before. It thus offers new perspectives but also brings new challenges. Indeed, the atmosphere, for instance, is not only located in the air, but its composition has an influence deep underground. It can be produced deep in the soil as well by the organisms that sustain this atmosphere. Similar unexpected findings are made by the scientists studying soil and rivers. The findings destabilise the predictions of models. In a complex way, the CZ shows that the composition of our

Earth is actively maintained by the interactions of organisms and matter, rocks, and water that cannot be easily simplified in the building of models. To overcome this shortcoming, the scientists carefully trace these interactions and unravel new dimensions of space and time. The CZ extends the pre-conceived boundaries of space by showing the various depths of the soil where many phenomena occur. The scientists then show that what we consider the surface, the horizon, is rather a line which never rests, which is always in motion, being weathered and eroded, never remaining stable. Scientists show that there is not only river at the surface, but that there are invisible watery paths at different depths, thus challenging the unity of what we consider a river to be. The Critical Zone opens up under-valued, under-observed time scales. For instance, the timeline over which a soil recomposes itself takes hundreds, sometimes thousands of years. It puts into question our human rhythm of soil destruction and excavation. Each entity on each territory follows its own timeline: the river for instance ages at depth, so that water of the same river does not have the same age throughout. The realization of such complexity raises concerns about our understanding of pollutants, for example, as they can stay longer in soils or rivers than predicted. Simultaneously as the CZ sciences destabilises existing models, it provides a different orientation for understanding the Anthropocene. As we saw in the chapter 2 “The Anthropocene and its views”, the Anthropocene is a disorienting time because of the incommensurability between human scale and geological time. Here, acknowledging the time and space scales of the multiple entities that compose the environment provides reassurance. Step by step, element by element, we can reconstruct an environment which “holds” together. The map of cycles that we designed in the chapter on visualisation attempts to provide this orientation in the Anthropocene. It shows how the different entities of the landscape hold together, forming cycles that shape the Earth. From form to cycle, reconceived and reconstructed maps suggest a conceptual framework to visualise the Earth.

As a result of the tracing of this new composition of landscapes, the Critical Zone brings a new understanding of the Earth’s connectedness. The conventional metrics are no longer relevant to understand how phenomena move through the CZ at Earth scale or even in a single watershed observatory. When scientists trace the elements, they do not trace them on a map because its metrics won't make them visible. Indeed, instead of close-to-close objects whose distance of separation can be easily ascertained and asserted, the phenomena that the CZ scientists trace travel through many places, passing through them, and so connecting these places in other than geographical ways. Connectedness describes better the way for an entity, an element, everything, to have an effect in more than one place. Therefore, two territories distant from each other could have undergone the same phenomena but with varied dramatic impacts depending on their particular environment. For instance, the atmosphere composed and emanated from one place can be felt at another distant place (as we saw in the Strengbach CZO with sulphur): these metrics cannot be measured because the phenomena are moving too fast. Or at the site scale, the near-depth is a blurred zone impossible to fit into stable, constrained metrics; the relationship between surface ground and the deep unaltered rocks changes all the time, and yet it is from the relationship that all nutrients for feeding organisms including humans are generated. Or take the example of rivers. The multiple cycles of the elements in the river cannot be framed by geography as they run from the pathways underground to the outlet of the river and beyond. The scientists show how disturbances of cycles can have an inertia: for example pollution in a river is felt far away from the source of pollution downstream. The scientists' research findings shed light on the impact of human activities on these signatures of natural cycles. It is as if humans were everywhere, inside little particles of nitrate added to the nitrogen cycles. We might therefore conclude that the social and technical habits of the Anthropocene can be seen through geochemistry.

We witness here what kind of knowledge can be gained from the CZ sciences, that very specific branch of the Earth sciences which, when it 'lands' on the ground, in sites, landscapes, and territories, is confronted daily with the disturbances caused by the Anthropocene. Without referring directly to Gaia, they consider biogeochemical cycles (characteristic of the Gaia Hypothesis) as the main component of their field of research. In this way the two notions, CZ and Gaia, are very close. To avoid confusion, we must reiterate here that this thesis is not intended to discuss earth science research and how it is framed or frames the Anthropocene as part of a broader debate on science. Here the framing is to bring CZ knowledge into the field of design to understand better the New Climate Regime. In the following section, we will discuss how this knowledge can be brought to design and how it fills a knowledge gap: the development of the cosmopolitical view and the understanding of Gaia in the design field.

8.3 Contributions

The thesis has developed a new understanding of natural entities, one which can enable architects to face the current and urgent situation of climate change. It showed how an ethnographic methodology is relevant for the field of architecture, bringing new and up-to-date knowledge from the CZ as a new domain of investigation for both architecture and social sciences. Conversely, the thesis has demonstrated how an architectural researcher could expand ethnographic methodology by using tools such as drawings and by focusing on different angles (such as space and territory). And here it is important to point out that this work differed from traditional visual ethnography (which uses visuals to capture what happens in the fieldwork with sketches, pictures or video; in this study the visualisations, the maps were developed in such a way as to better convey the knowledge and analytics that have been unravelled in the ethnographic fieldwork. The visualisations designed and described in the chapter 'Mapping the Critical Zone' were indeed an additional and new product to accompany the conventional 'thick descriptions' of the scientific practices.

8.3.1 Architecture and Landscapes in the Anthropocene

The Anthropocene literature in the field of architecture mainly focuses on geological relationships between rocks and humans (Turpin, 2013; Ellsworth and Kruse, 2013; Denizen, 2013; Tyszczuk, 2018). Other authors offer an in-depth reading of social sciences theories dealing with the Anthropocene (Grosz, 2013; Frichot, 2018; Krasny & Fitz, 2019; Krogh, 2020). The thesis extended these two approaches to the Anthropocene and deepened the reflection with empirical data. First, it showed that there are many other relationships than those of humans and rocks which are necessary and now available for understanding the Anthropocene, therefore broadening and bettering the scope of discussion and action concerning the whole of the climate crisis. Conversely, as the debate on the Anthropocene focuses mainly on the atmosphere composition in climate discussions, the Critical Zones expands the relationships to consider soils, rivers, trees, organisms, chemical reactions, etc. The thesis demonstrated how these relationships bring new dimensions to the Anthropocene issue, particularly the embedding of human activities and their impact on bio-geochemical cycles. Thus, it brought awareness to the importance of cycles and their impact on our understanding of space, depth and time. Secondly, the thesis brought evidence from the fieldwork to the social sciences theories that architects are familiar with (Haraway, Stengers, Latour). The thesis indicated how it is possible to describe differently the environment, territories, and the Earth, bringing a new knowledge on nature/landscape to architects so they could design differently in the future.

The thesis echoed many of Tsing's arguments on landscape theories that are found in her broader work on landscape ethnography and her dialogue with other scholars (Tsing, 2017b; 2021). Landscape ethnography could be described as the study of landscapes through ethnographic methodologies, following the various relationships between humans and non-humans and describing landscapes through this perspective. The thesis expanded Tsing's arguments, extensively developing them in chapter 2. As Tsing has shown, we effectively live in ruined landscapes and thus their description is essential. In the empirics, we have witnessed as a reality, "phantom acreages" (as described by Pomeranz, 2000 and Charbonnier, 2021), the disappearance of soils, and the shrinking supplies of water. The findings of this thesis followed the body of works studying damaged landscapes.

Most of Earth's reactions to human activity escape our will. Attempts at mastery of life via bio- or geoengineering appear reckless. Moreover, organisms shape their environments as architects do (as Coccia, 2019, reminded us) but in ways that cannot be predicted with certainty. The CZ scientists know this by carefully designing their model to authorise this uncertainty. We have seen that heterogeneity is everywhere, each entity is variable. We cannot apply one solution through scales or even one solution for one entity as the assumption of unity is put into question (recall the many rivers for example). Therefore, this thesis set up the need for designing at Earth scale, assuming connectedness between the Earth and the territory. Unsurprisingly, this type of ambitious program has yet to be developed, although some of its characteristics have been listed above. They clearly distance themselves from bio- and geo-engineering as ready-made solutions that perpetuate the anthropocentric view, as this view does not discuss the agencies and unexpected trajectories of entities other than humans. Instead, this study within the Critical Zones argued for a more humble and inclusive mode of practice within the pluriverse, where the metrics are not the ultimate referents and where other-than-humans time and space scale dimensions are needed (the biogeochemical cycles, framing differently the dimensions of space and time, bring this awareness); where there are many more entities in the cosmopolitical view; and where practices of observation, instruments, newly developed maps and tools are necessary to shift pre-conceived modes of representations. As we realize how difficult it is to design for ruined landscapes, it is important to acknowledge unintentional design by other creatures and to use more carefully scalability procedures which inappropriately used are killing ecological relationships.

At this point we can ask how the new knowledge about the Critical Zone puts in question the theorisation and design of parks, cities and buildings. First, this knowledge addresses the notion of 'context'. Context is a well-established concept in design, used to assess the relationship between a design and its environment. But what if there is no stable background, and therefore no context (which now appears to have been an unjustifiably pre-unified notion)? Second, it questions the design use of materials and entities which we previously considered as passive and simplified: water or trees in cities or parks, excavated soil, building materials extracted from the ground, all of which are moved 'easily' without resistance within a conventional design project (e.g. trees from a nursery to their project location). What if instead we consider that these elements already have capacities for action, agencies, a trajectory on Earth, multi-species relationships? What if we had not seen their resistance before and now feel the consequences? Third, the CZ questions the notion of ecosystem services to resolve human-environment relationships via economisation, as it does the convenient ecological compensation zones that allow one place to be destroyed if it is restored in another place. We know that ecological relationships are very much tied to a specific place in order to thrive (in collaboration with other species). Thus, extraction means death in most cases. In answer to these questions we know that in future design the multiple ingredients and compositions of nature (their fluidity and chemical variability) should be taken into account, instead of presuming a static and unitary vision of soil, river or atmosphere. In this way designers will be able to trace many cosmopolitical adjustments from within the many new compositions available as elements of design.

8.3.2 The Cosmopolitical view

Set alongside the claims of authors gathered around the cosmopolitical view (Stengers, 2010; Latour, 2004b, 2010; Tsing, 2015; Yaneva and Zaero-Polo, 2015), the findings of this thesis showed that the environment is indeed complex: the heterogeneity of the soil is measured at every meter, the variability of chemicals in a river change daily, unexpected quantities of beings make the air breathable. The findings of this thesis put in question the view of a unified nature and bring back into discussion the diversity of the elements that compose soils, rivers, and the atmosphere. In this sense, the findings fit the same definition of the cosmopolitical developed by the proponents of this view. However, the thesis also provided new evidence towards this view by using the ethnographic methodology. The methodology used by some of the authors cited above (Latour, 1988, 2005, 2013; Yaneva, 2009, 2019; Tsing, 2015) enabled me to produce a cosmopolitical account of the decomposition and re-composition of nature. While the volume on cosmopolitical design by Yaneva and Zaero-Polo, and the exhibition catalogue *Making things public* (Latour) provide many examples of cosmopolitical design, this thesis contributes an especially granular understanding of cosmopolitics based on our fieldwork in the CZ with scientists.

This was achieved by the application of Actor Network Theory and STS methods, by following the agents of the CZ—scientists, instruments, and entities. It validates ANT as an efficient methodology for tracing the environment, now no longer as a stable background but as a moving field. Indeed, the ethnographic fieldwork brought details and new elements with which to illustrate what a cosmopolitical engagement with nature implies: expanding it by showing how rich this approach could be if one extensively detailed the agency of the many entities composing the environment of the CZ—the space that they create, craft, and compose, the time over which they evolve, and importantly how we can observe them. Utilizing the ANT and STS methods, the findings of the thesis demonstrated that there is no stable background, no pre-established landscape into which a design can be fitted. Thus do we see that nature is a *composed* entity which needs to be mediated by the instruments the bring to light different versions of what we had considered being the "universal" and unitary. Through field surveying, the land is redefined. We learn that there is no objective soil, river or atmosphere waiting to be discovered. The instruments change the nature of the 'site': it exists through the instruments and encompasses several visions as versions of itself.

The observatory is thus a specific place where we can witness cosmopolitics. The observatory appears as a matter of concern, a Ding, a Parliament of Things where scientists are representatives of natural entities. Herein lies the politics in the renewed understanding of nature that they introduce: we must take into account, encompass more entities in the management of territories than was previously recognised by the anthropocentric view. These entities are not at all passive but react to human behaviour and act in their own way. The observatory is an example of how different disciplines come together on the site to exchange knowledge. The observatory itself becomes a place of politics; it allows the situating of these entities around which humans gather. The variety of disciplines gathering in an observatory could easily be extended, including designers, in a perspective of collaboration.

Maps made from the anthropocentric point of view may reduce the understanding of natural entities. By contrast the findings presented here demonstrate that there are different versions of a soil. The thesis strengthened the critiques already addressed against pre-conceived cartographies that operate 'from above' and tend to fix a version of the territory once and for all (Nagel, 1986; Grevsmülh, 2014, 2016; Farinelli, 2009; Latour et al. (2010); Olwig, 2008; Brotton, 2013). Compared to the knowledge gathered on the natural entities from the CZ, the conventional cartographic representations of them seem limited indeed. Entities seen from the geographical point of view are ordered in a space that we presuppose as being empty and abstract, and measured according to a single metric (one that makes them scalable). On the contrary, in the empirical chapters we have been able to trace each entity with its own scale. Consequently, one territory extends as far as the entities that compose it are connected. By contrast the river with a source, a shape and a soil-land separation appears as a geographical artefact. The counter view established in this thesis reinforces the body of works from practitioners who are experiencing new modes of visualising landscape entities—through the degree of wetness for the river, for instance (da Cuhna, 2018; Bremner 2021). This thesis thus continues some experiments started by practitioners who shift away from cartographies which take natural entities for granted: da Cunha who puts in question the cartography of rivers; the Monsoon research group led by Bremner who maps atmosphere, rain, and sediments; and Forensic Architecture that traces chemicals in the atmosphere. These authors show how the manner of representing these entities shapes territories, controversies, conflicts and inequalities. In contrast to the perspective from the outside (which produces anthropocentric visualisations), cosmopolitical visualisations of a territory introduce more dimensions in both the collection and sharing of multiple viewpoints.

The thesis showed how the instruments deployed by CZ scientists create this particular cosmology of the natural world by enabling the observation and visualisation of the many entities that compose it, following the work of historians of science (Daston and Galison, 2007; Ait-Touati, 2012). In this way the Riverlab, the instrumented tree, the Gravimeter, are cosmograms, as they produce an image that describes the cosmology of these entities. According to Tresch (2005, 2007, 2020), cosmograms make ontological arrangements accessible. In this sense they are a research tool and can help us understand entities we design within our field of architecture. Through its use of empirical findings, the thesis brought a more concrete definition of cosmogram than was available before. For instance, the Riverlab transforms the river from a single entity into a myriad of components that, as they flow, change a landscape. The Riverlab allows this vision of nature to be shared with a community. The Riverlab operates as a cosmogram because it not only makes this variability visible, but it also connects the micro-world - the microcosm - to the macro-world - the macrocosm (Descola, 2016). Indeed, we now understood how chemical molecules are linked to the whole watershed, to the river and its profile, to its flow through the territory. Similarly, trees as studied in the CZ, bring together the micro-world, bacteria, fungus, etc., and the macro-world, the atmosphere. Each cosmogram unites the microcosm and the macrocosm in its own way. When we follow the decomposed natural elements, we change scale because each element has its own way of scaling the earth. Thus, an observatory makes the incommensurable world commensurable. For example, by composing the river as music, we hear and see the different chemical molecules that make up a river. Or by showing a soil at the scale of the earth or the earth at the scale of a soil particle, inverting the macro and the micro. And cosmopolitics lies precisely in the ability to recognise that different species have their own patterns, behaviours, relationships and scales following De la Cadena and Blaser (2018) or Viveiros de Castro (2014) on the pluriverse.

The socio-technico maps developed in the chapter “Mapping the Critical Zone” aimed at expanding this visualisation of the Critical Zone and assembling the various cosmograms. They demonstrated the necessity of being equipped to grasp this new knowledge, to observe and understand the entities’ behaviours. Cosmopolitical visualisations are cosmograms; they suggest seeing “from within” in opposition to cartographies “from above”. Therefore, the thesis has suggested the importance of developing cosmopolitical visualisations[108] with this experimental work at mapping the Critical Zone. Cosmopolitical visualisations don’t show forms but picture “signatures”, traces of impacts left by natural or human activities on a specific territory. They are dynamic rather than static and about relationships rather than objects.

8.3.3 STS and Gaia theory

The findings resulting from the use of the ANT method and inspired by the STS in this study confirmed the effectiveness of these theories and methods for thinking about the complex relationships between humans

108 I had started thinking in this direction and published preliminary results in an article “Giving depth to the surface” and a book “Terra Forma”

and non-humans - objects or living beings. The overcoming of the subject/object, nature/culture dichotomies has indeed been at the heart of the ANT methodology from the beginning, the overcoming achieved by following the different actors, concerns, and controversies. The issue of the Anthropocene, which is shaking up the relationship between the collectives and their environment, gives credit to the ANT and STS approaches as effective means of understanding these evolving relationships.

However, as most of the authors in STS follow laboratory work, this thesis provided another perspective on the field in natural sciences. It extended the STS and laboratory studies to the CZ observatories which are very special kinds of labs in the field. Science studies scholars have been showing since the 1970s how scientists work together and with their instruments, showing a slower science as they exchange hypotheses, share a worried perplexity, and cultivate ways of being attentive to each other's questions. The difference here has emerged from the site of research itself and the relationship of the scientists to it. The CZ observatories survey the Earth but not by extracting pieces of it to bring them to the lab in a single move. On the contrary, the scientists continue their work in the field at the same time as work proceeds in the laboratory; it is as important as the latter. This is especially true as new instruments are created to specifically follow the variations of the entities in the field and as they adapt their practices to these rhythms so as to follow the flows and exchanges.

Thus, this study continued the work on STS visualisation (Galison, 2014) to address the field of Architecture (Yaneva, 2014). The visual perspective translated the arguments into easily understandable graphs (as the network mappings for example). Notably the visuals were used to emphasise the importance of the instruments in the daily practices of the scientists: they allow them to see, to understand the world, and shape a particular cosmology. This cosmology distances itself from the naturalistic regime and moves towards the regime of Gaia. Forms don't matter as we have shown that landscapes can be decomposed into many entities, each of them following various paths and modes of existence. The thesis brought some arguments to Gaia Hypothesis (Lovelock, 1979; Margulis, 1998; Latour, 2017a; Lenton, 2020; Dutreuil, 2016) and its efficiency for understanding the New Climatic Regime, as the Anthropocene notion seems to limit a cosmopolitical perspective. The thesis thus also contributes to making the Gaia Hypothesis more accessible with the descriptions of the fieldwork that we have provided.

The experimental maps based on the findings of the fieldwork and developed in chapter “Mapping the Critical Zone” didn’t show the forms of the entities but rather their paths, the tracing of these entities through the Critical Zone. The thesis expanded on how to approach Gaia theories by offering its cartography through the Critical Zone: a gaia-graphy. The gaia-graphy underlying the whole argument of the chapter “Mapping the Critical Zone” and embodied in the socio-technical and habitability maps of cycles offered a reading as to how human disturbances affect territories and how tools can be developed to tackle this issue in future design projects. They showed the “Gaia territories” (Latour, 2017a); that is they showed how to observe the terrestrial reactions locally, how to trace them, and how to visualise them so as to elaborate new design strategies for these territories. The maps of the cycles, or the gaia-graphy, addressed the question of the Earth’s habitability, as does Gaia theory: what are the limits to habitability, and what processes might make ruined land habitable again? In a way, we are not only inhabiting a space, but we inhabit cycles; we inhabit times.

These visualisations are a design work in themselves as they reorganise entities according to different scales and metrics, bringing a new form and content to landscape spaces. Maps give architects better tools to understand environmental issues, as they are the main access to knowledge of the territory and are mainly used to design a project. They are therefore central in the design practice, especially in the territorial strategy of the landscape, so that their frame of reference conditions the future shape of the territories. The use of these different cartographic tools would thus make it possible to modify the frame of reference of the design used by architects or urban planners, by paying more attention to the depth of the soil, to its hydric quality, or to the composition of the atmosphere, or even to the cycles that maintain the environmental conditions. These mapping methods were tested in different contexts during my PhD. In pedagogy, in workshops with architecture students at ETH Zurich and EPFL Architectures schools

(Switzerland), at the University of Minnesota College of Design School of Architecture USA, and at the Architecture, cities and territories School in Marnes la Vallée (Paris France). In research workshops with professionals in the construction materials sector (especially quarries), and with the Paris urban planning agency (Institut Paris Région) during a commission for the architecture and landscape biennial in Versailles spring 2022. Or in research workshops with scientists from CZ at the IPGP and at the Museum of Natural History in Paris with the support of the Centre des Politiques de la Terre (IdEx Université de Paris, ANR-18-IDEX-0001). I have also published in architectural journals (NESS, OASE 110, Stream, Les Cahiers du paysage) and book chapters ("Traveling through the Critical Zone", ZKM catalogue Critical Zones. The Science and Politics of Landing on Earth. Publisher: MIT Press. Editors: Bruno Latour & Peter Weibel and "The Critical Zone observatory space", in Infrastructural Love: Caring for Our Architectural Support Systems, edited by A.Carbonell, H.Frichot, H.Frykolm, and S.Karami.) and in the peer-reviewed journal GeoHumanities ("Inside the Critical Zone." 2020 DOI: 10.1080/2373566X.2020.1803758). These experiments consisted of describing a site, a part of the Earth with a new perspective. They have not been linked to more traditional, project-based modes of landscape practice, but they may be in the near future, as the company I co-founded is now in charge of an urban planning project in Nantes (France). What needs to be paid attention to is the interface with scientific practices in order to keep in each cartographic design project a space to integrate this knowledge in order to continue a living collaboration between science and design.

Making a visualisation of Earth's habitability could provide architects with a tool to expand their expertise from spatial to time-sensitive design and allow them to deal better with the sensitive issue of Earth habitability at the time of an Anthropocene in which floods, fires and storms destroy the habitats of the more-than-humans. These maps can be used by designers, architects, planners, landscape architects, but also by politicians or institutions in charge of developing territorial strategies. Thus, they offer a way of understanding, reviving and perpetuating the concept of Gaia to better qualify the Earth at the time of the Anthropocene.

8.4 Prospect for further work

The limitations of the study are directly related to the scope of the ethnographic investigation. Indeed, as CZ science is place-based epistemic communities of geoscientists working in specific socio-natural settings, other non-scientific communities also inhabit and work in these places. But due to time and resource limitations, I chose to focus on scientists because I wanted to fully understand what they do in the field, what instruments are used and for what purpose, and what they visualise differently. I chose to focus on expert knowledge, hoping to extend the scope of the investigation to other forms of knowledge from local people, foresters, farmers, NGOs, etc., i.e. non-expert knowledge, as Stengers (2010) would call it in a true ecology of practice perspective, as part of the continuation of this work.

A possible way of developing and enriching the present work would be to conduct more studies with the other communities who are part of the territories where the CZOs are situated. To further develop the work, more interviews with the local communities, farmers, landowners, and ecological movements, could be conducted to bring their concerns to light. This further work would enable us to understand the full cosmic complexity of those issues. Moreover, to follow the activities of more actors, in more places, would produce a larger portfolio of cosmopolitical maps. Indeed, other actors bringing other instruments, put other procedures in place to grasp and understand these territories. Their results would surely complement the socio-technical maps of the CZ. The new visualisations would bring new understandings to the design fields of research, new awareness of the new climatic regime and would entice new forms of action.

I will have the opportunity to extend the scope of the ethnographic investigation of Observatories through a post-doc that I will start after my PhD at IPGP as part of the national research project Terra Forma. TERRA FORMA (Equipex+ 2021-2029) aims to design and test observatories of the Anthropocene, based on new technologies (IoT, AI) and on a broad participation of the territory's stakeholders (from citizens to companies). I have submitted a project to follow the development of this new equipment in observatories where inhabitants and ecologists are also involved alongside scientists, using the same methodologies as my PhD with mapping as well. My research proposal is to follow the implementation of these sensors in the field, which will be carried out by scientists but also by citizens and stakeholders, in order to understand how they shape or not a more cosmopolitical way of governing territories, more attuned to the “intrusion of Gaia”. The research will explore how these in situ sensors are generating new knowledge about the earth, shaping new scientific spaces, providing massive data and addressing global climate issues. How does the Critical Zone generate new communities around observatories? How can they be traced? On a more prospective level, the proposal also addresses the question of the visualisation of these territories: what are the relationships between the big data provided by these sensors and the collective imaginary on the Anthropocene? For this task, we will use alternative cartographies as a means to elicit new definitions of spaces and to make visible the different forces at play in territories recomposed by the Anthropocene. This intersection between the humanities and the life and earth sciences could lead to new and fruitful developments. Indeed, the development of these sensors will involve the public in their development or/and the collection or/and reading of the data. It is therefore important to follow the whole process of the project and to draw the consequences of the implementation of these new sensors for the territorial policies, in particular through cartographies of these new sensor systems. These maps also aim to define with the scientists what an Anthropocene Observatory is (what are the expected variables and indicators). The implementation of the sensors depends on two things: the scientific questions that can be co-constructed and the field constraints. The contribution of the cartographies should make it possible to answer the following questions: how to translate, transfer or co-produce a scientific research project that can be shared both between experts and with the public (the challenge of democratising access to technology and information)? The aim will be to question what is the visualisation and/or communication of data from new sensors: what are these new possible visualisations? How do we communicate the data? What would be the process of assimilating data and knowledge? Among the objectives of these maps are the embodiment of global issues in a local narrative that takes into account the links between human and non-human collectives, both in its material, cartographic and emotional dimensions (attachment to the territory). And finally the description of equipment with new infrastructures enabling both the scientists and citizens to collect new signals, lift the veil of invisibility, facilitate ubiquity in order to seize hot spots and hot moments, and increase points of view on this unknown and suddenly reactive earth, these territories in metamorphosis that will be explored with these new sensors.

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Appendix

Interview guide for scientists of the Critical Zone

1. Can you describe your practice: what is your field of research, your affiliation and your observatory? What are you studying? (research question, territorial issue)
2. What is your daily work routine? What instruments do you use, what are they used for? What is the one you use the most? Can you show me or describe how it works on the site?
3. What are the parts of the Critical Zone that you are studying at the moment? How do you connect them? Are you studying a specific cycle in the Critical Zone?
4. Can you make a list of the different entities you find in the Critical Zone? What are the most important ones that play a crucial role in what you are studying? Are there any hidden parts that you suspect play a role?
5. Have you seen any changes (good or bad) in the landscape / Critical Zone that you have been studying since the beginning of your practice?
6. Do you produce images for your research? Can you show me some of them?
7. I will show you a visualisation of the Critical Zone I made, it is a diagram I drew at the beginning of this research. May I ask you to draw on this model?

- First, can you correct the thickness of the CZ layers and describe their materiality?
- Secondly, can you retrace the cycle(s) you described to me earlier?
- Finally, can you name the factors that drive these cycles?

Table of interviews

Scientist /discipline	Lab/institution	CZO	Interview	Ethno obsv	Interest	Issue/worry
Jerome Gaillardet Geochemist	IPGP - CNRS	OZCAR network	IPGP 20170717; 7p. (3700w) 20180917; 7p. (4000w) 20190117 ; 3 h., 7p. (3700w) 20190918 ; 1 h., 6p. (3200w)	CZO Guadeloupe Team streams exploration for biogeochemical sampling	The boundaries of the CZ; rocks weathering; terrestrial biogeochemical cycles; rivers & mountains	To understand the distinction between abiotic/biotic processes; the Anthropocene
Isabelle Braud	INRAE	CZO Lyon		OZCAR days Sète	Hydrology of urban watersheds, modelisation	Water resources, water uses
Paul Floury Geochemist	IPGP - Extralab (start up Riverlab)	CZO Orgeval CZO Strengbach	Station F (office) 20191111; 3h., 14p. (8675w) + sketchs	CZO Orgeval & CZO Strengbach, Riverlabs manipulation & data	Real-time, high -frequency; chemistry of rivers	To miss chemical elements that could have major impacts (flooding, pollution)
Sylvain Pasquet Geophysic	IPGP Post-doc	CZO Strengbach CZO Guadeloupe + others	IPGP 20190912; 1h10; 6 p. (3450w) + sketchs and images	CZO Guadeloupe, geoseismic campaign; IPGP daily work	Shallow rocks/soil; instrumentation of the network	To reduce the myopia of the depths of the CZ
Sylvain Kuppel Hydrophysicien	IPGP - CNRS post-doc INRAE	CZO Strengbach CZO Bénin CZO Bretagne CZO Inde	Remotly (zoom) 20200408; 1h40; 12 p. (5650w)	OZCAR days Sète Model computor demonstration (zoom)	Transversal model of the CZ; interaction water at depth-soil-trees	To understand how trees use water; drought
Eric Gayer Geochemist	IPGP	CZO La Reunion	IPGP Conversation notes about 1000w (interview to do)	AGU talk, San Francisco	Influence of wearther on erosion and geomorpholy	To understand how soil loses matter
Group session	IPGP	CZ representation	Jérôme Gaillardet, Eric Gayet, Paul Floury, Julien, Mathieu, 20170717 – 11p. (5300w).	IPGP, work group, interactions	How to explain the CZ to other scientists?	The disparition of the CZ as a scientific object
Marie-Claire Pierret Geochemist	OHGE Strasbourg	CZO Strengbach	OHGE lab office 20190711; 1:05; 5 p. (3000w) + drawings	CZO Strengbach routine campaign July and March; Archives tour at the lab	The collaborative work; the cycle of Sulphur	To keep good relationships with the other actors on the site; Acid rain and forest decline
Jacques Hinderer Geophysic	EOST Strasbourg	CZO Strengbach	EOST office 20200117; 1:15; 6 p. (3400 w.)	Gravimeter demonstration	Gravimetry; time; hydrology	Waterground drought and land subsidence
Nolween Lespages Geophysic	OHGE Strasbourg	CZO Strengbach	OHGE lab office 20190711; 55min; 4 p.	Model computer demonstration	Waterflow paths at the surface; modeling the soil	Waterground drought
Anne-Désirée Schmidtt Biochemist	OHGE Strasbourg	CZO Strengbach	OHGE lab office 20200306; 10min; 1000w	Chemistry manipulation: white room, spectometer	Nutrients transfert soil - biomass (calcium)	Nutrients depletion in the soil (because of acid rain)
Solenn Cotel Hydrogeologist	OHGE Strasbourg	CZO Strengbach		CZO Strengbach. Collect of sediments & lab analyse	The sediments in the river	Excessive amount of material in waters.
Pierre Pedologist	OHGE Strasbourg	CZO Strengbach		CZO Strengbach. Soil samplings	Composition of soils	Nutrients depletion in the soil (because of acid rain)

Scientist /discipline	Lab/institution	CZO	Interview	Ethno obsv	Interest	Issue/worry
Charlotte Le Traon Geohydrologist	PhD Rennes University	CZO Bretagne CZO Guadeloupe	Guadeloupe 20190528; 56min + Poster AGU, SF	CZO Guadeloupe, geochemistry team	Waterflow paths at depth	
Jean Marçais Mathematician	IPGP	CZO Puerto Rico (Luquillo)	Puerto Rico 20190603; 30min	CZO Puerto Rico, field visit CZO Guadeloupe geophy	Waterflow paths at depth	Links between sciences & land policies
Gilles Brocard geomorphologist	Genoble University	CZO Puerto Rico	PR conversation notes	CZO PR, geoseismic campaign	Islands geomorphology	Soil erosion, landslides, tropical storms
Jennifer Druhan Hydrologist	University Illinois	CZO Eel River CZO Shalle hill, US	Guadeloupe 20190601; 41min; 6 p. (3500 w)	CZO Guadeloupe, geochemistry team + AGU talk, San Francisco	CO_2 storage by trees at depth	Unknown quantity of CO_2 that can be released if forests decline (fire, drought, storm, exploitation)
Lou Derry Biogeochemist	Cornell + IPGP visitor	Former Director of CZO National		CZO Guadeloupe, geophy team	Developing models for biogeochemical cycles	
Lin Geochemist	China			CZO Guadeloupe, geochemistry team	Uranium sampling, new device testing	
Bill MacDowell Biohydrochemist	New Hampshire	CZO Puerto Rico (Luquillo)		CZO Guadeloupe, geochemistry team, CZO PR tour guide on the field	Biotic chemical composition of river	Storms, asphyxies of tropical rivers, response to hurricanes and droughts
Kayle research engineer	Puerto Rico (Luquillo)	CZO Puerto Rico (Luquillo)		CZO PR, tour of the site, biochemical sampling		
Bianca PhD biochemistry	Puerto Rico (Luquillo)	CZO Puerto Rico (Luquillo)		CZO PR, tour of the site	She told us historical colonial stories & native stories	Storms, asphyxies of tropical rivers, response to hurricanes and droughts
Janne Willenbring Geologist	San Diego California	CZO Puerto Rico (Luquillo)	Poster session Puerto Rico	CZO PR trees behaviors	How erosion affect landscapes	Trees recovery after storms
Dan Richter Biogeochemistry	Duke University	CZO Calhoun		Film: The Education of Bruno Latour: On the Anthropocene	Global biogeochemical cycles	
Susan Brantley Geochemist	Pennsylvania university	CZO Shalle hill, US		AGU talk SF	Fondation of the CZ network	Gap lab / field

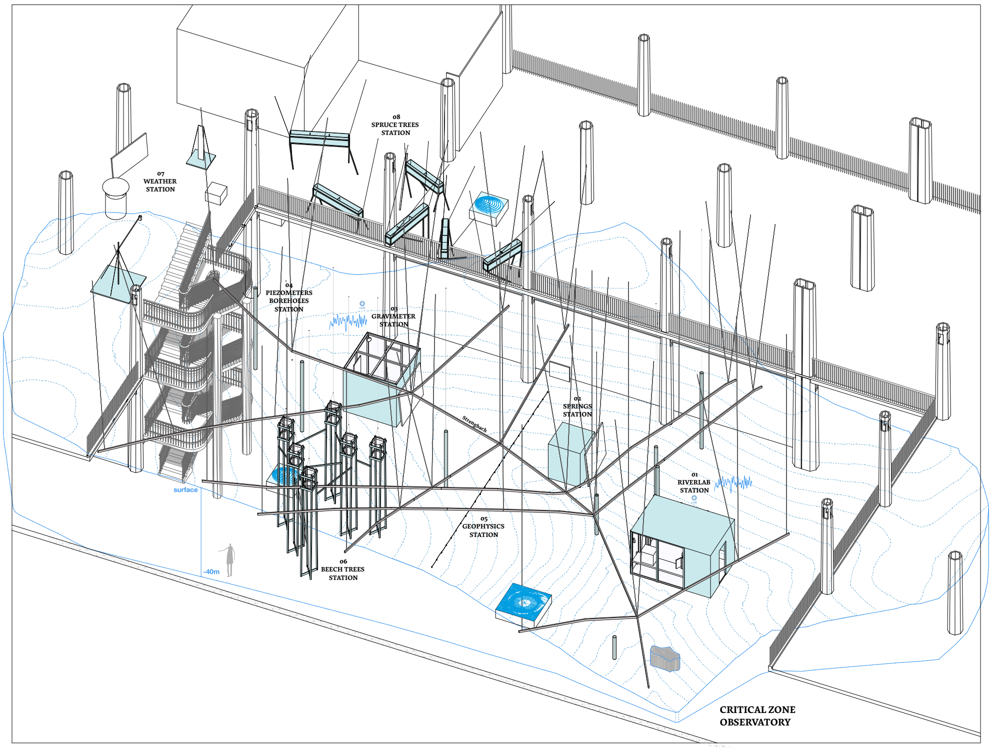
Exhibition

The CZO space installation at the ZKM

With my studio SOC (Société d'Objets Cartographiques), we imagine an art and science space based on some of my thesis research findings. After a long investigation of the Strengbach observatory in the Vosges forest impacted by acid rain, we reconstructed this watershed observatory inside the museum. But none of the traditional features of a landscape—trees, slopes, topography, river—were represented. Instead, we reconstructed the network of instruments that scientists use to understand the responses of this specific watershed to environmental disturbances. Our installation aimed to give the public an opportunity to experience an encounter with these new optical instruments by navigating from one instrument station to another, following rivers, soils, and trees with a new gaze. Artistic mediation and documentation are mixed with the images produced by scientists to develop a dialogue that fosters ways of becoming sensitive to the movements of the earth.

Alexandra Arènes & Soheil Hajmirbaba, studio SOC. 'CZO Space'. *Critical Zones. Observatories for Earthly Politics*. ZKM, Karlsruhe 2020-2022.

Photo credit © ZKM | Videostudio


08
SPRUCE TREES
STATION
07
WEATHER
STATION
04
PIEZOMETERS
BOREHOLES
STATION
03
GRAVIMETER
STATION
02
SPRINGS
STATION
01
RIVERLAB
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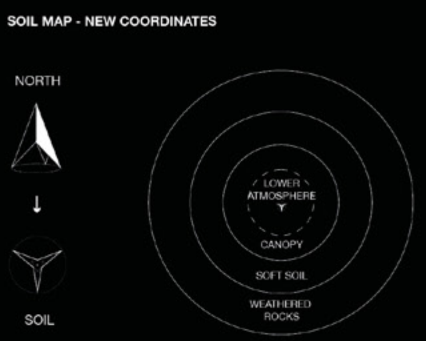
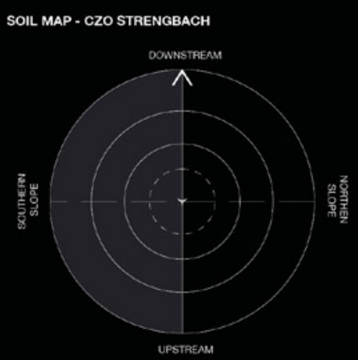
GEOPHYSICS
STATION
06
BEECH TREES
STATION
surface
-40m
CRITICAL ZONE
OBSERVATORY





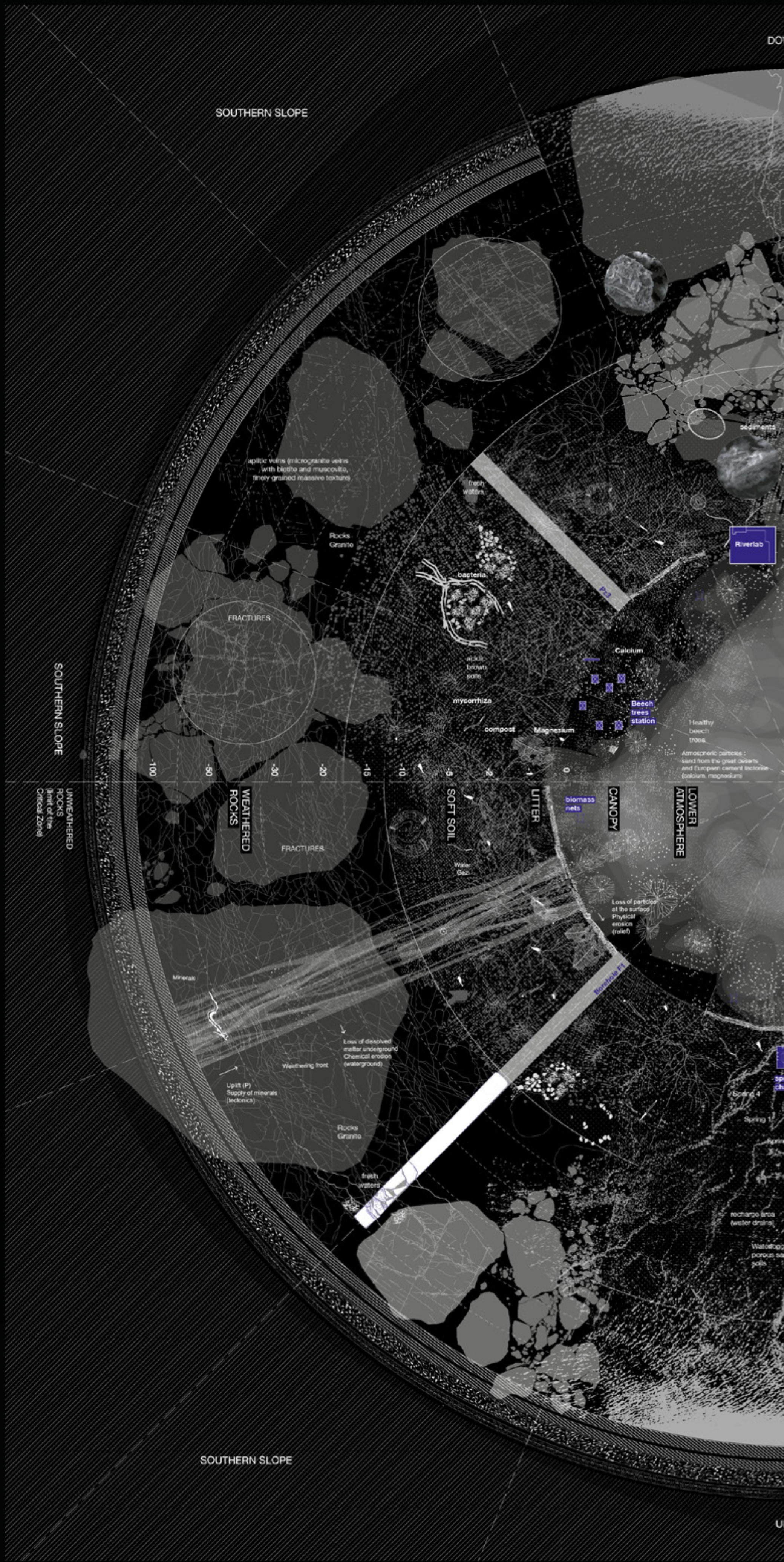
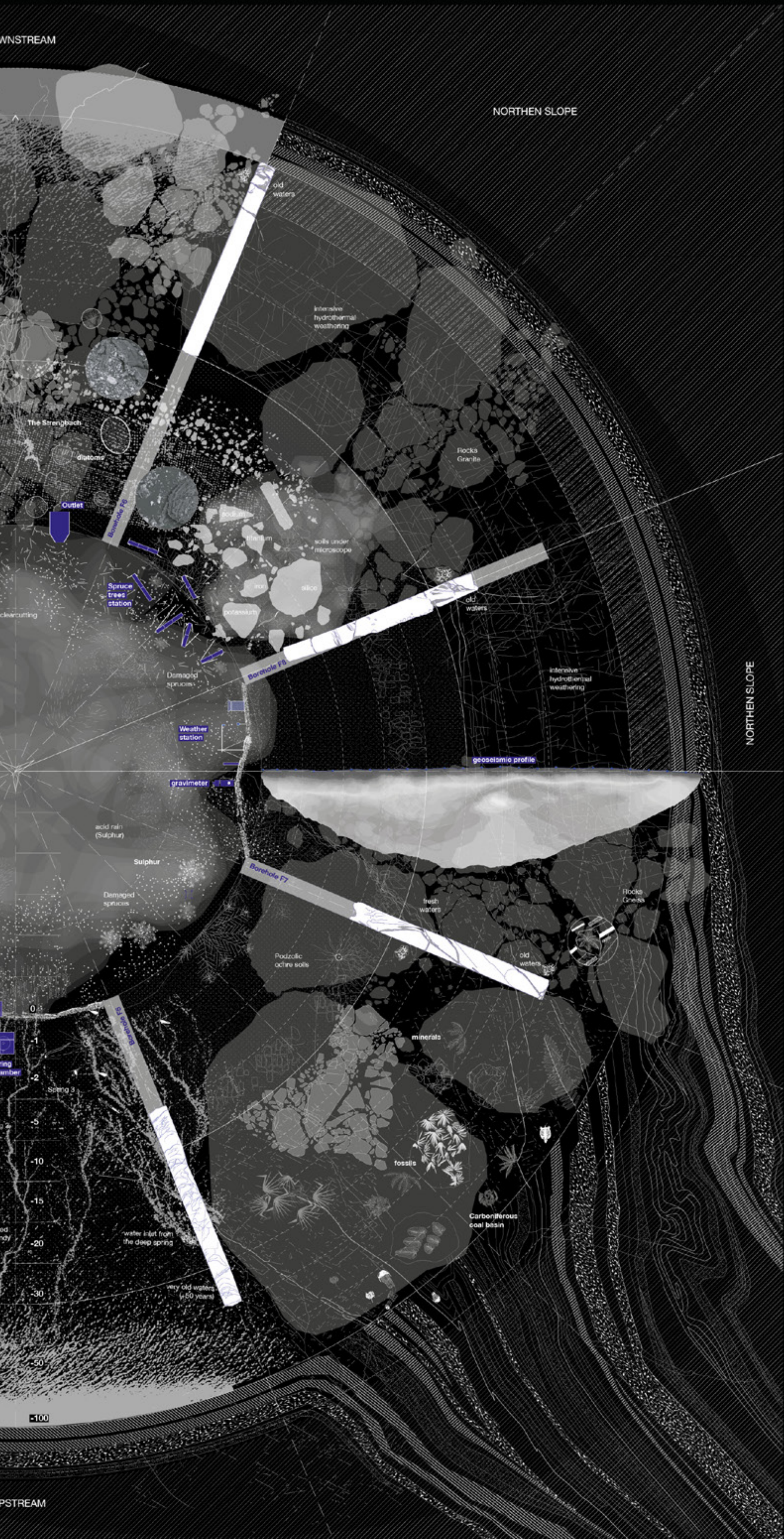
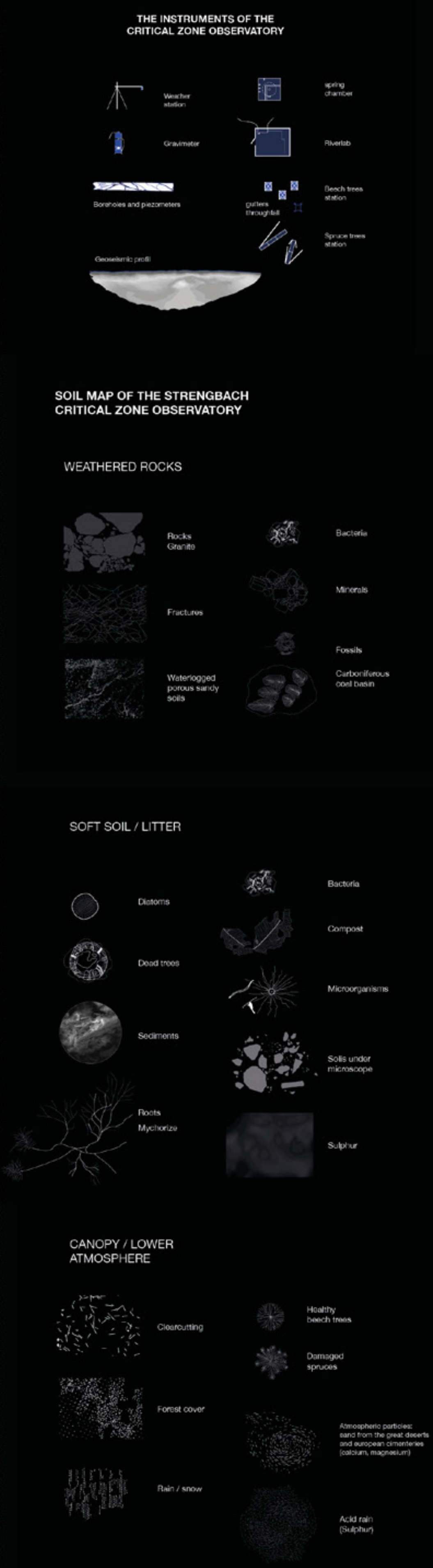


Image credit © Alexandra Arènes | Studio SOC, Soil Map of the Strengbach Critical Zone Observatory, exhibited at the ZKM Museum for Art and Media, Karlsruhe, for *Critical Zones. Observatories for Earthly Politics*, 2020-2021.



WNSTREAM
NORTHEN SLOPE
old waters
intensive hydrothermal weathering
The Strengbach
diatoms
Rocks Granite
Outlet
Borehole F6
Spruce trees station
soils under microscope
clearcutting
old waters
Borehole F8
Damaged spruces
intensive hydrothermal weathering
Weather station
NORTHEN SLOPE
geoseismic profile
gravimeter
acid rain (Sulphur)
Sulphur
Damaged spruces
Borehole F7
fresh waters
Rocks Gneiss
Podzolic ochre soils
old waters
minerals
fossils
Carboniferous coal basin
water inlet from the deep spring
very old waters (+50 years)
-100
PSTREAM



THE INSTRUMENTS OF THE CRITICAL ZONE OBSERVATORY
Weather station
spring chamber
Gravimeter
Riverlab
Boreholes and piezometers
gutters throughfall
Beech trees station
Spruce trees station
Geoseismic profil
SOIL MAP OF THE STRENGBACH CRITICAL ZONE OBSERVATORY
WEATHERED ROCKS
Rocks Granite
Bacteria
Fractures
Minerals
Fossils
Waterlogged porous sandy soils
Carboniferous coal basin
SOFT SOIL / LITTER
Bacteria
Diatoms
Compost
Dead trees
Microorganisms
Sediments
Soils under microscope
Roots Mychorize
Sulphur
CANOPY / LOWER ATMOSPHERE
Clearcutting
Healthy beech trees
Damaged spruces
Forest cover
Atmospheric particles: sand from the great deserts and european cimenteries (calcium, magnesium)
Rain / snow
Acid rain (Sulphur)

The author

Alexandra Arènes is a French landscape architect (Ecole National Supérieure d'Architecture de Grenoble, 2008). She worked as a project leader for six years in a landscape architecture firm, Baseland in Paris, where she developed territorial planning and landscape research. She then followed SPEAP (MA in political arts) at Sciencespo, Paris, directed by Bruno Latour, before co-founded SOC (Société d'Objets Cartographiques) in 2016, a think tank on earth political design, drawing on scientific and public enquiries, and producing workshops and exhibitions. The studio designed the installation CZO space at the ZKM (Museum for Art and Media, Karlsruhe) for the exhibition *Critical Zones. Observatories for Earthly Politics* (curated by Bruno Latour), the result of close collaboration between science and art. She has also contributed to theatre research (*INSIDE, Back to Earth, Où atterrir?*), and co-authored the book *Terra Forma, Manuel de Cartographies Potentielles* (B42, 2019).

BOOK

2019 - *Terra Forma, Manuel de Cartographies Potentielles*, with Frédérique Ait-Touati and Axelle Grégoire. Edition B42.
English version: *A book of Speculative Maps,* February 2022, MIT.

WRTITTING Articles/chapters

2020 – "Traveling through the Critical Zone", ZKM catalogue *Critical Zones. The Science and Politics of Landing on Earth.* Publisher: MIT Press. Editors: Bruno Latour & Peter Weibel
2020 – "Inside the Critical Zone." GeoHumanities Journal. DOI: 10.1080/2373566X.2020.1803758
2018 - "Giving Depth to the Surface – an Exercise in the Gaia-graphy of Critical Zones", The Antropocene Review, 29 June, 2018, with Bruno Latour and Jérôme Gaillardet.

EXHIBITIONS

2020-2022 – "Critical Zone Observatory Space", installation at ZKM Center for Art and Media, Karlsruhe, in *Critical Zones. Observatories for Earthly Politics*, curated by Peter Wiebel and Bruno Latour. May 2020 - February, 2022.

RESEARCH GRANTS

2020-2022 – "Terra Forma, mapping the cosmopolitics of the Earth". Centre des Politiques de la Terre, IdEx Université de Paris, ANR-18-IDEX-0001
2020-2021 – "Où Atterrir?" Projet Pilote dans la Région Centre, France. Ministère de la transition écologique et solidaire. With Bruno Latour et S-Composition.
2019-2022 – PhD Candidate "Architectural Design at the Time of Anthropocene: Reporting from the Critical Zones" at The University of Manchester, School of Environment, Education and Development, Department of Architecture. Supervisor Pr. Albena Yaneva. SEED funding.

LECTURES

2021 - Landscape seminar series, ESALA Edinburgh, « Terra Forma, investigating Critical Zones », February 24, 2021.

2020 - Goldsmith Lecture, University of Texas, Architecture. Alexandra Arenes, “Learning from Critical Zones,” September 30, 2020.
2020 - Lecture Series: Institute of Landscape and Urban Studies. Architecture of Territory, Prof. Milica Topalović, Critical Zones: Sensors for Ghost Landscapes, October 01, 2020.

[Epilogue]

Landscape forms when a fungus encounters a rock it eats to extract calcium and phosphorus to produce and exchange sugar with a root, that grows a plant, that shades for a grass, that a deer eats and, as it treads on the ground, it lifts the earth and moves the worms below, a few centimetres lower, which helps fungus to produce soil over it by breaking down the organic matter of the dead deer and the faded plant. Landscape forms when plate tectonic diverge a few thousand kilometres underground, causing groundwater to flow out of the trough left by the gap itself, pushing the rising and folding soils a few hundred kilometres further before their tops erode and their sediments flow into the river created by the same movement**. Landscape forms when forgotten hydrocarbons spill underground where bacteria transfer them in nutrients for the plants, who grow and crack the slabs and walls of the industries that formerly housed the tanks, which they mycorrhize and erode with fungi that will feed new plants, that will attract the bees and their berries the birds, and their shadow the humans***.*

* "Forests emerge as assemblages through mycorrhizal connections; trees with mycorrhiza form forests. See Curran (1994) "The Ecology and Evolution of Mast-Fruiting in Bornean Dipterocaraceae: A General Ectomycorrhizal Theory." PhD diss., Princeton University.
** Jérôme Gaillardet, (1999) Global silicate weathering and CO_2 consumption.
*** Gilles Clément (2004) Manifeste du Tiers Paysage.