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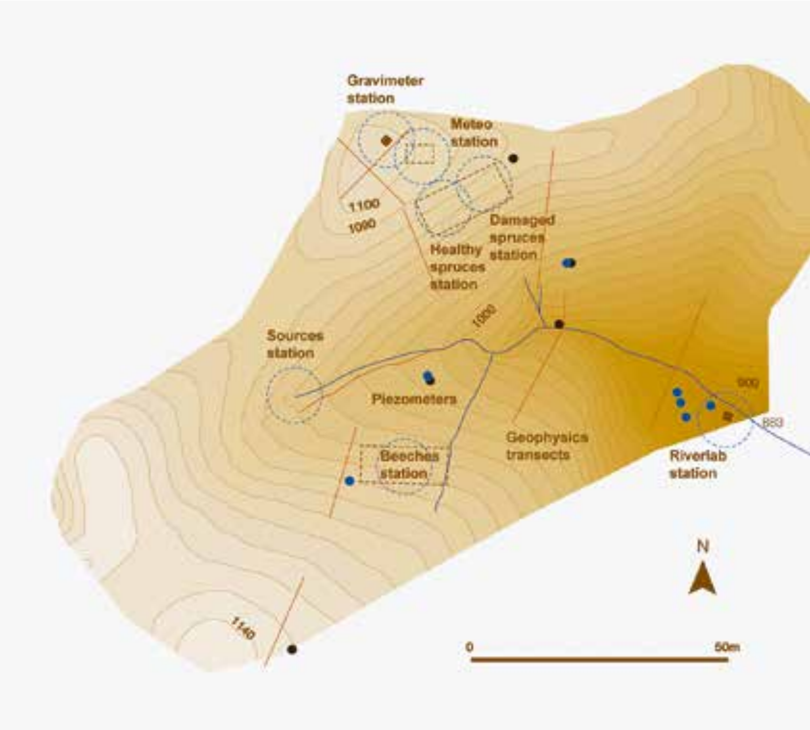


Traveling through the Critical Zone

1 The village of Aubure lies at an altitude between 800 and 900 meters.
2 The scientists call this "a budget."

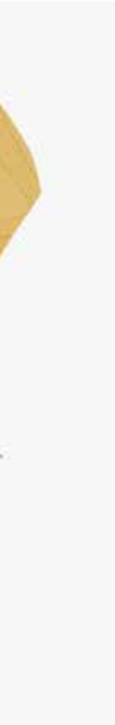
Alexandra Arènes

INTRODUCTION: WATERSHEDS. Foxgloves, bark beetles, acid rain. The forest is toxic and yet very quiet. During the walk, there are troubling patches: clumps of foxgloves — lethal flowers — in the clearings, a tree stripped bare here, a whole stretch of dead forest, dry and earth-colored there (*see fig.* A). It's very hot on this July day. The 30°C bar was crossed last week. Yet, the village of Aubure, near the monitored forest with its instrumentation, is one of the highest villages in France,[1] nestling in the Ballons des Vosges, a dense forest, "black" like its German counterpart a few miles away; a forest of shade with harsh winters.

Two days before, Marie-Claire (see Pierret, this volume, 136–9) took us with her on her tour of the site, which consists in gathering the measurements made at each of the stations — that is to say, the places with instrumentation — in the catchment basin. The first station is the meteorological one. A Critical Zone Observatory (CZO) is first and foremost about calculating the quantity (of water and elements) which enters, minus what exits from the system, and hence everything that happens in between.[2] The meteorological station is the entry point of the system, the high point from which to deduce the other measurements, the registration of all the parameters that heat, cool, feed, ventilate, humidify, and recharge the catchment basin and which, in the case of the Strengbach CZO, enable the scientists to follow the evolution of the impact of acid rain.

A catchment basin is a geographical unit that receives a quantity of water and runs it off from its hillsides or slopes into a common outlet. Drainage divides mark the limits between catchment basins. A catchment basin isn't a legal entity or an administrative territory, but a geological entity in which water circulates, sometimes at depth, in a particular way. Their size, morphological characteristics, and occupancy of land may be variable, but a catchment basin is recognizable as such because it is a sort of receptacle for water, and is, therefore, in that sense, the living ground of the beings it irrigates. A watershed becomes a CZO when it is equipped with — often discreet — machines that register the pulsations and dynamics of the Critical Zone.

Thus, a CZO is never obvious as such; it is always a host of distributed instruments that enable us to recognize it (*see fig.* B). As we shall see, these tools provide a new understanding of nature. There is no river, there are levels of wetness, clouds, molecules, and chemistry. There is no ground, there is water around grains of sand. What is this new understanding of nature that substitutes the Critical Zone for the classical notion of landscape? What are the tools, methods, techniques, and practices required to produce the sciences of the Critical Zone? In what way does this enable us to better understand the Earth and our way of inhabiting it?



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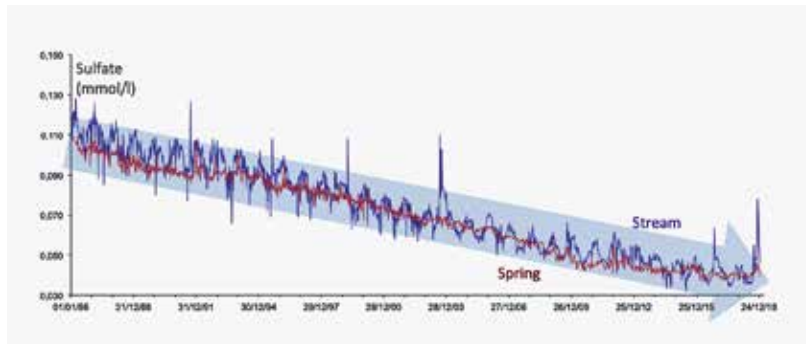
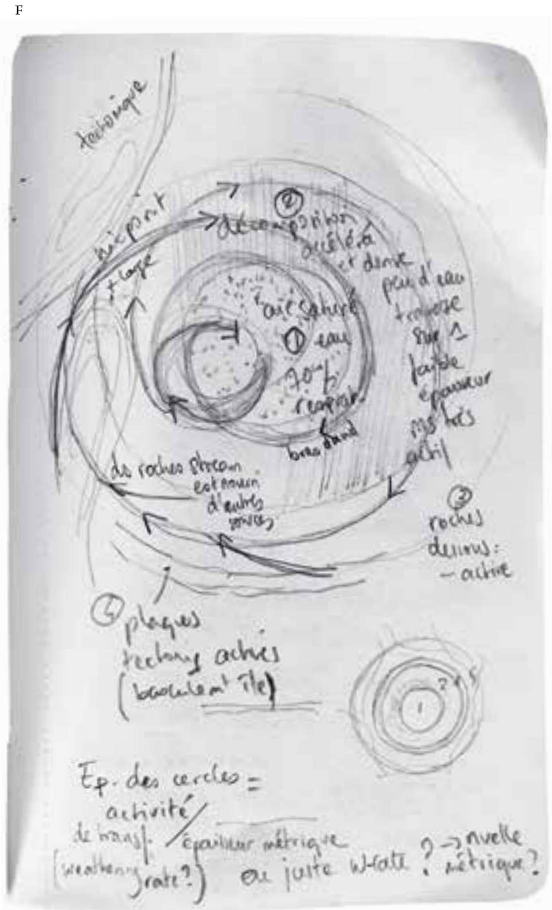


FIGS.: A — **The Strengbach forest, 2019.** B — **Alexandra Arènes, Map of the Strengbach CZO, 2019. Visualization.** C — **Soheil Hajmirbaba, The meteorological station at the Strengbach CZO, 2019. Drawing.** D — **The station of damaged spruces, 2019.** E — **Sulfur chronicles. Variations/decrease of sulfate (SO_4^{2-}) concentrations since 1986 in the stream at the outlet and in spring (drinking water) at the Strengbach catchment.**

Story 1: Trees

MARIE-CLAIRE records the temperature variations printed by an automatic arm on the graph paper. It has been unusually hot for a moderate-altitude mountainous environment. She adds that this doesn't mean the winters are less harsh: it is just as cold, but there is more rain, at the expense of snow cover. Yet, groundwater tables are recharged thanks to snow cover here. Marie-Claire is worried about the drinking water supply for the village — and for the thousands of other villages in France and towns worldwide. This is one of the research issues here, as local as it is global. Marie-Claire goes round the various instruments in the enclosure, which is protected from animals and humans (*see fig.* C). She picks up the water bags, but there are just a few drops in them; it isn't worth noting the quantity. We carry on with her round. A few meters from there, there's the spruce station. Large horizontal metal trays perched on slender legs are set up among the trees. Marie-Claire explains that these big steel rays, perched on their precarious vertical legs, harvest the rainwater that has fallen on the branches and needles of the pine trees (the "throughfall" (*see fig.* D)). In the lab, her team compares the chemical composition of the rainwater that has escaped contact with the trees with 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 that results from industry releasing sulfuric acid into the atmosphere? Do they manage to produce more nutrients than they lose? Scientists, answer these questions and make some disturbing findings: on the one hand, the anthropic emissions of sulfur from Asia that cause 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 feeding the Vosges forest are brought in with the sand from the great deserts (for example, the Sahara). I notice something strange at the station and exclaim: "You measure the rainwater beneath the canopy, but the trees around the gutters are dead!" Marie-Claire explains that these gutters have been there for some ten years or so, but that an epidemic of bark beetles — Scolytinae — a common parasite in our latitudes, but one whose life cycle has speeded up with global warming, is developing, and virulently attacking the trees. Particularly as these trees are already fragile due to the acidity of the soils and the increasingly long and frequent drought episodes. The soil acidity is not only a product of acid rain, which has in fact decreased since the 1980s although its effects are still felt (*see fig.* E), it is also due to the very nature of the spruce trees whose acidic needles carpet the soil with a cover that promotes acidity. The spruce trees are trapped in this mortuary bed, a dramatic situation maintained by the industrial forestry activity that continues to plant spruce in order to fell and sell them. The gutters await in the void, perched on their sloping ground facing the mountain, as if suspended in the sky. A mist hangs over the watershed this morning and heightens our feeling of vertigo.

F



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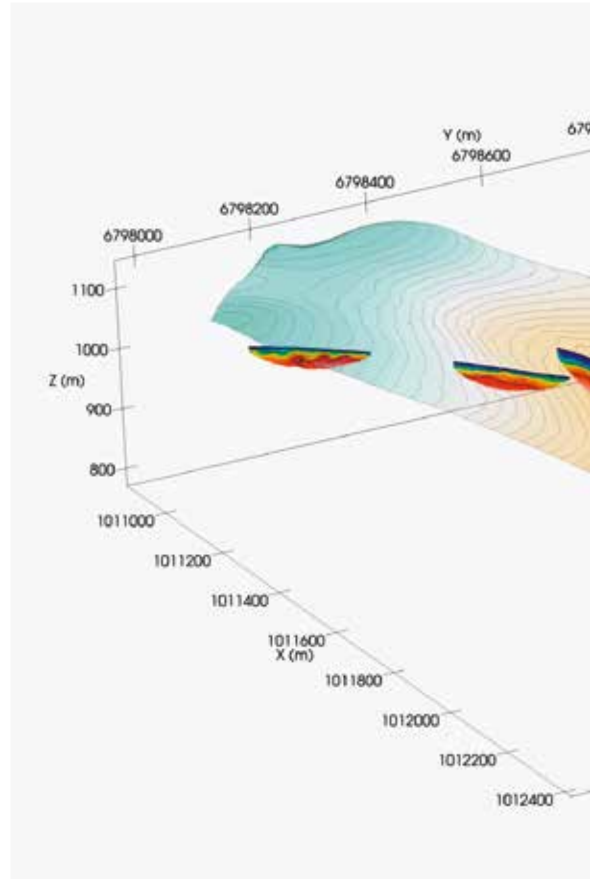


3 Field book entry by Alexandra Arènes. Translated from the French.
4 A place in a stream bed where a nick occurs due to a change of tectonic level.

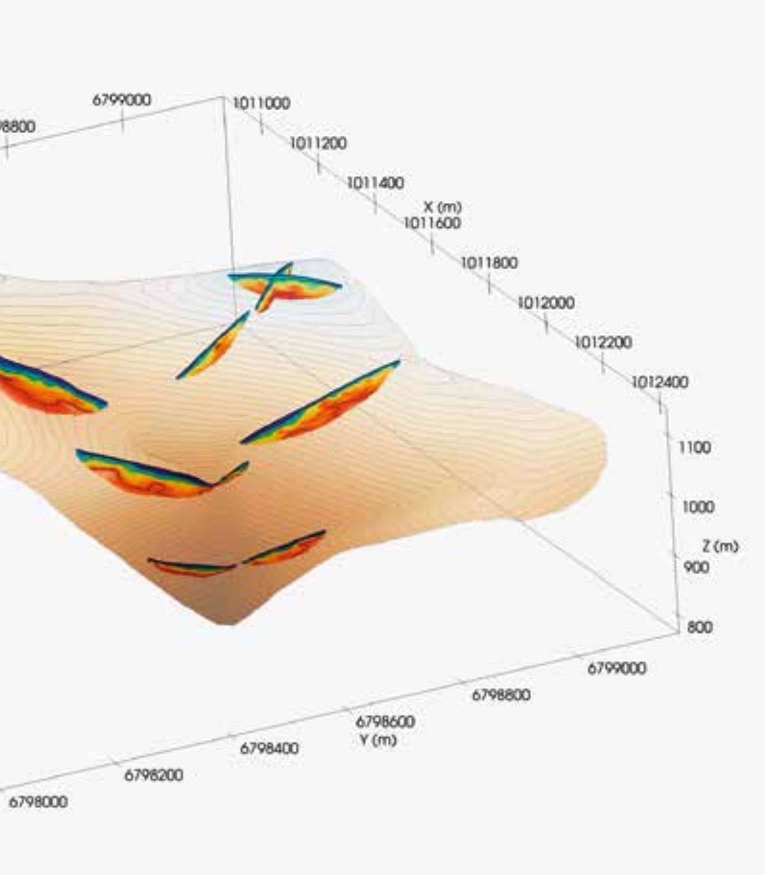
Story 2: Water

WE MOVE TO another instrumented spot. Marie-Claire measures the flow and temperature of the four springs of the watershed. 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. I learn from several other interviews that water has different ages. Some waters are termed "fossil" because they remain stuck deep in the rocks for hundreds of years. 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. So researchers are creating models to understand the water pathways. To do so, they need to know the precise composition of the Critical Zone and therefore to travel directly to the field.

Extract from the field visit, Guadeloupe CZO, Bras-David river (*see fig.* F):

> Rainforest: indeed, it is pouring rain. The space here is water particles: the water is not only in the flow of the stream we climb, where we slide and end up being totally wet, but also in the pores of the ground, the water is also in the heavy air, as the trees breathe loudly around us. Jérôme reminds me of the explorer Humboldt; he moves rapidly through the jungle. He and his team make rough drawings out in the field, note the location of a place of interest. This is a kind of exploration, but not *in extension*, to discover new lands (since there is no longer a square meter of Earth's surface that is unknown), but an exploration to discover the intensity of the changes, reaction, and movement of the Earth. It is all about registering small intensities occurring on the surface (an eroded rock, water with a high ion content) that are "echoes" of major (biogeochemical or hydrological) cycles. The scientists are therefore not mapping places but points of transformation.[3]

Water flow paths are among the most challenging features 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: the surface layer of the Critical Zone (commonly called the soil and containing organic matter) 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," which are a kind of tube,



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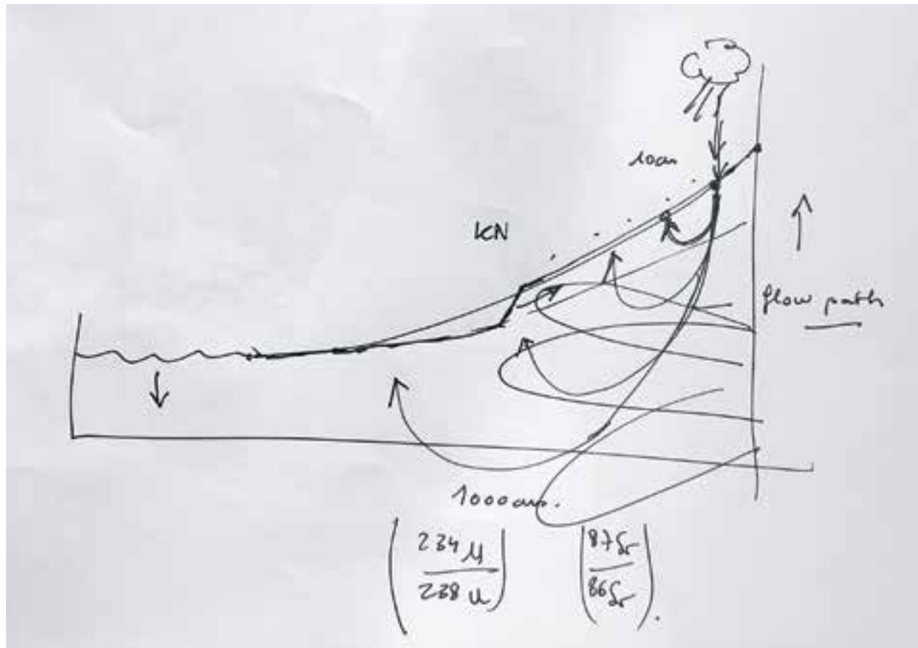

F — **Alexandra Arènes, Sketch of the cycles in the CZO Bras-David, Guadeloupe, 2019.** G — **Geophysics campaign, Seismic characterization of the Strengbach catchment, August 2019.** H — **Sylvain Pasquet, Seismic velocity profiles in the Strengbach catchment, 2019. Visualization.** I — **Jérôme Gaillardet, Sketch of the water paths and knickpoint in the CZO Bras-David, Guadeloupe, 2019. Drawing.**

opened up by mammalian activity or the decomposition of a root.

We are, however, blind to these depths unless geophysics and geochemistry afford us a glimpse of what is going on beneath our feet. Geophysics allows us to visualize the location of the porous regions (*see fig.* G), while geochemistry provides hypotheses on these trajectories by studying the chemical composition of the spring water or the water collated at depth by the piezometers. If the water pathways are so important to discover, this is because the water carries chemical elements. Driven by solar energy, the water activates the cycles of the biogeochemical elements that end up transforming landscapes. The surface is easier to understand. At depth, however, the Critical Zone is much more complicated; in this case, the images are simplified and are forced, in a way, to synthetize the features; such as these colorful transects that Sylvain showed me at the IPGP which render the porosity of the soil (*see fig.* H). By contrast, geochemistry is an exercise in acupuncture. Essentially, the idea is to multiply several measurement points (the more differences there are, the better the data), as I learned by exploring the rivers with the team that measured conductivity upstream and downstream, in order to choose the river to study that offers the most contrasting measurements (before/after knickpoint[4] (*see fig.* I)). The differences and heterogeneity enable them to see better what is happening beyond the reach of sight. They register the variations, the alteration, the erosion. It is these processes that actually give the Earth its heterogeneity by constantly modifying the chemical composition of the planet.

Instruments enable the scientists to plot the variability of the natural elements. By taking small extractions from what they call the different "compartments," they isolate micro-events that generate changes. By extracting a leaf or taking a sample of water, they can isolate a molecule and trace the sulfur cycle; by generating a wave in the ground, they can observe a vibration and reconstitute the depths of the Critical Zone. By noting and tracing these small events, they deconstruct a monolithic vision of the landscape. The landscape is not a space to be filled, nor inert matter that can be shaped at will, but a volume of phenomena, entities, movements, and reactions: with cycles that animate it. The sciences of the Critical Zone shift the anthropocentric view of nature as a background to human actions, and restore the complexity of what constitutes a territory, of the entities that compose it, element by element. The landscape has quite another "shape," composition, granulometry, and dynamic. The instruments, sensors, and tools recompose "nature," pixel by pixel, across the cycles and the connections between agents. By cross-checking data, ordering micro-events, the scientists see all the disturbances, sometimes even micro-changes, that would not be perceptible on a human time scale or with the naked eye, but which nevertheless generate a virulent reaction within the system.

J

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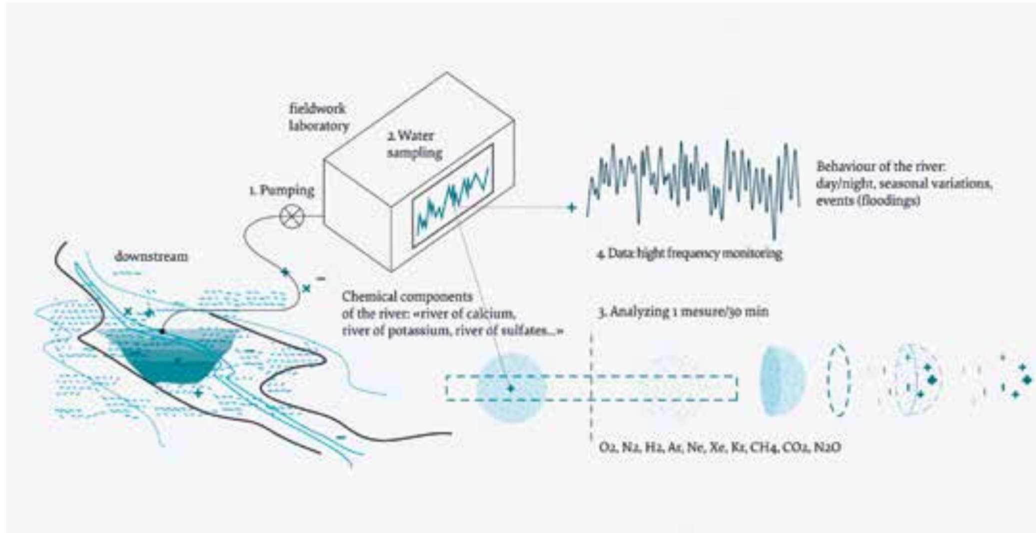

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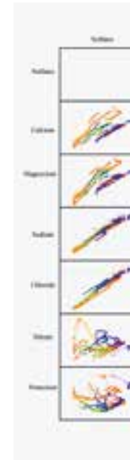


M

5 See the contributions by the Critical Zone scientists in this volume; Pierret, 136–9; and Gaillardet, 122–9.

6 Nils Ole Bubandt and Anna Tsing, "An Ethnoecology for the Anthropocene: How A Former Brown-coal Mine in Denmark Shows Us the Feral Dynamics of Post-industrial Ruin," *Journal of Ethnobiology* 38, no. 1 (2018): 1–13, here 8.

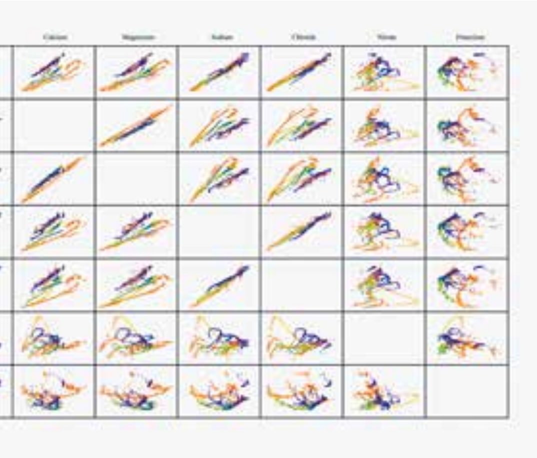
7 Cosmogram, in the sense developed by John Tresch, "Cosmogram," in *Cosmogram*, ed. Melik Ohanian and Jean-Christophe Royoux (New York: Lukas and Sternberg, 2005), 67–76.

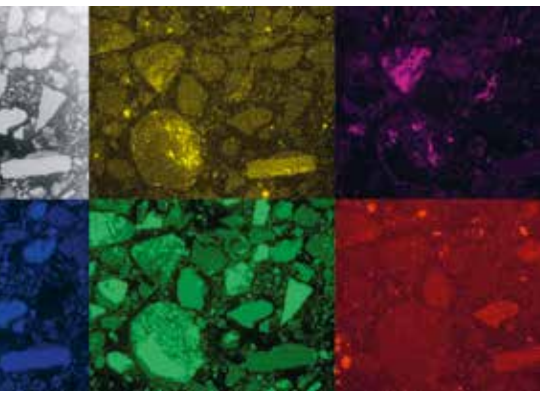
8 This visualization has been described in Alexandra Arènes, Bruno Latour, and Jérôme Gaillardet, "Giving depth to the surface: An exercise in the Gaia-graphy of critical zones," *The Anthropocene Review* 5, no. 2 (2018): 120–35.

Story 3: Cosmograms

HOWEVER, why should we be interested in such unremarkable sites? It isn't here that the glaciers are melting, the forests burning, or emblematic species of wild fauna going extinct. No, these aren't hotspots of the global crisis. The CZOs are, above all, places of life, a nearby territory that is dying slowly and discreetly. We also need those scientists who look carefully at the environments closest to us. For Solenn, the challenge is to amplify the site — that is to say, to collect different measurements, since everything interacts and moves without regard to boundaries. The CZOs are special because they are inhabited — and have been for many years — and because issues have emerged from concerns that relate to both human and nonhuman assemblages, bonds that maintain the ecology of a site.[5] The CZOs enable us "to notice the complicity at stake in the political ecology of humans and nonhumans,"[6] as Tsing and Bubandt say. This is what can be described as cosmopolitical, those unheralded actions that nevertheless constitute the most mundane and ordinary territories all over the world.

WE GO A BIT FURTHER down the Strengbach and come to the Riverlab. The Riverlab is a prototype in situ laboratory, sheltered inside a container and located on the river bank (*see fig. J*). It measures various river parameters continuously: its chemistry, physical properties, and sediments (*see fig. K*). These continuous measurements have uncovered significant and irregular chemical oscillations between day and night, particularly during heat waves, to the point that researchers call these phenomena a "nychthemeral concert" (*see fig. L*). In the Strengbach, we find a different tune. The river is very heavy with sediment, particles of matter that obstruct the instruments that have been placed in the river to take measurements and send water into the Riverlab. The river doesn't make itself easy to monitor. We go into the Riverlab. The researchers set the machine going. It spits, groans, and begins to work. The pressure is too high and it chokes. 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 we took measurements manually, calmly, and in silence. Bringing a fully equipped laboratory onto the site was not without its problems, both human and technical. However, when Jérôme and Paul explain to me how Riverlab works, I can glimpse the potential that is there. It is a kind of temporal chemical microscope that enables us to see all the variations of the river: seasonal variations, diurnal and nocturnal variations, one-off variations (floods). 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 is what there is inside it — its particles, its molecules — that appears on the





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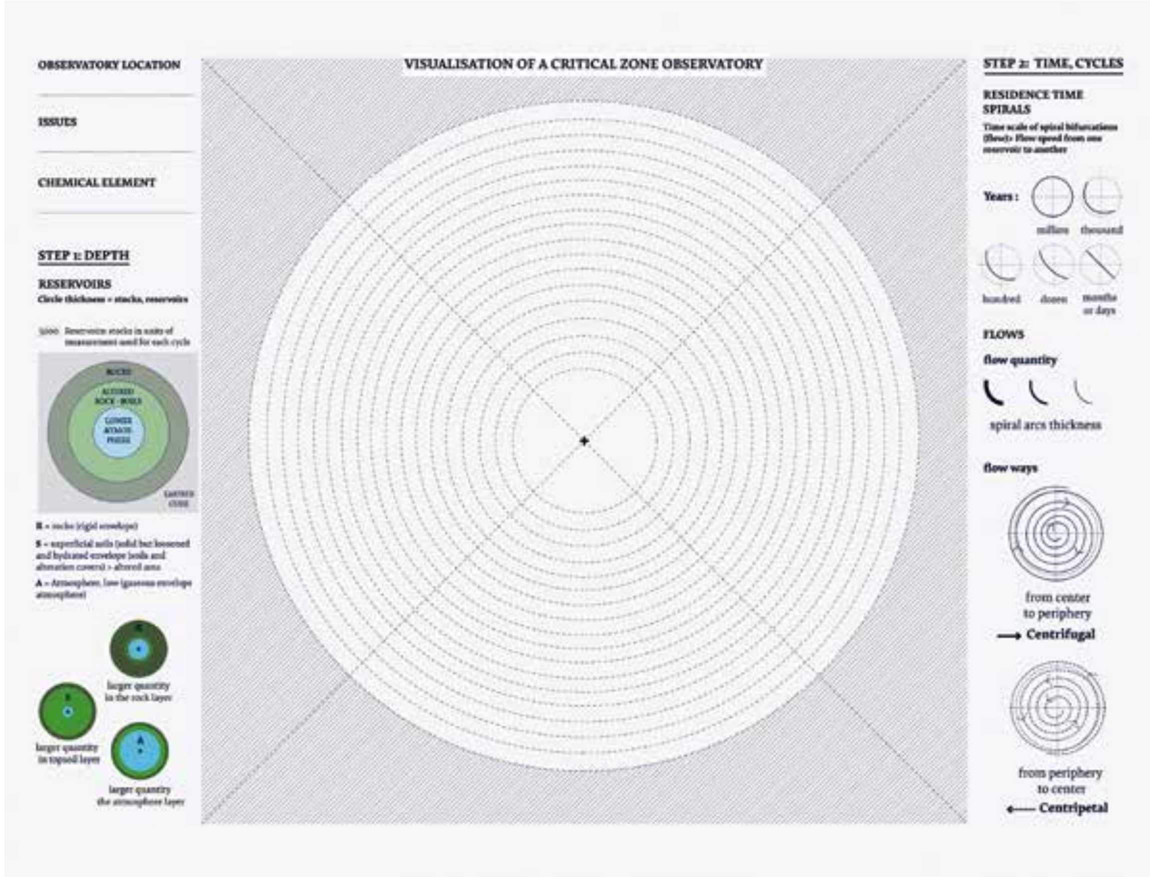

J — Interior of the Riverlab, CZO Strengbach, 2019. K — Alexandra Arènes, Scheme of the Riverlab data acquisition, 2019. Visualization. L — The geochemical matrix or the orchestra of the elements in the river of the Orgeval CZO. Each color represents a flooding event. M — Scanning Electron Microscopy (SEM) images of a soil sample from a spruce plot in the Strengbach watershed. The different colors correspond to the areas of concentration of different elements (yellow: titanium, violet: iron, blue: potassium, green: silica, red: sodium) N — Alexandra Arènes, template for the visualization of the Critical Zone, 2019.

graphs in the form of waves which the scientists know how to interpret. To me, it is pipes, valves, taps, test-tubes, and a computer. Yet I can see that the Riverlab is a true cosmogram[7] that takes us right into the Critical Zone.

On the last day, I have a meeting at the laboratory of the Hydro-Geochemical Observatory of the Environment (Observatoire Hydro-Géochimique de l'Environnement, OHGE) in Strasbourg. Extracts and samples from the observatory fill the basement of the building: these are the biological and geological archives, including the rock cores drilled to a depth of 120 meters during the installation of the piezometers. The tubular rock cores, extracted by boring, are laid out in large cabinets and labeled with their depth of extraction. This is a dive into the depths, but horizontally this time! We pass through the ages and the strata, we follow the faults — those fractures where water circulates in the granite, although that rock isn't porous to water — which complexify the understanding of the Critical Zone at depth. Naturally, at these depths, we must not think of clear, free-running water: as Jérôme reminded us, water is wet grains. Other cabinets contain surface rocks, bags of branches and bags of leaves, a fridge full of water samples, and shelves loaded with soil samples. There are also microscopic images of sediments, showing traces of organic and mineral material. The Strengbach CZO is there, too, its natural history is there, but it is not preserved as in a museum; it is consulted and archived here only because the aim is not to freeze the site in time, but to understand how it changes.

We climb the floors of the building. All trace of naturalistic materiality has disappeared here. The flasks of soil, organic matter, water, and rock are digitized, then converted into light rays (*see fig.* M). The Strengbach takes on quite another form. The geophysics maps are drawn up from the propagation of seismic waves or electromagnetic signals. There is the animated map of the recharging of the spring, the map of the surface water runoff, the map of electrical resistivity, and the map of porosities across the whole of the watershed. The raw digital data do not give an image. The world is made up in this way of contrasts that one may choose to ignore or accentuate. The combination of these measurements is represented figuratively, particularly because geophysics is linked to the spatialization of data. This is not quite the case with geochemistry, which follows changes through trajectories, that is to say, the trace of an element surveyed in the Critical Zone. However, on my excursions into the Critical Zone, I have never seen a suitable solution for mapping the biogeochemical cycles. Therefore, we have begun to develop a visualization tool to map the processes of the Critical Zone (*see fig.* N).[8]