Introduction

Linking microscopic mechanisms to macroscopic behaviour across scales

In Earth sciences, as in science more broadly, the development of knowledge is often described through a series of major intellectual shifts: from early conceptual and philosophical approaches, to observation, experimentation, and more recently, numerical modelling. While such a chronology is necessarily simplified, it highlights a progressive enrichment of the ways in which natural phenomena can be investigated. Today, these approaches coexist and interact, forming a complex and evolving scientific landscape.

This volume is published at a symbolic moment: nearly one hundred years after Jean Perrin was awarded the Nobel Prize in Physics in 1926 for his work providing decisive experimental evidence for the atomic nature of matter. In *Les Atomes*[1], Perrin wrote:

« Deviner ainsi l'existence ou les propriétés d'objets qui sont encore au-delà de notre connaissance, expliquer du visible compliqué par de l'invisible simple, voilà la forme d'intelligence intuitive à laquelle […] nous devons l'atomistique »[2]

Although written in the context of atomistic physics, this reflection still resonates strongly today. Not because it suggests a direct relationship between atoms and the macroscopic properties addressed in this book, but because it expresses a broader scientific ambition: to seek, beneath observable complexity, the elementary mechanisms from which physical behaviour emerges. The work presented in this volume follows this line of inquiry, while extending it through a multiscale approach in which the connections between microscopic mechanisms and macroscopic behaviour are built progressively across intermediate scales.

In my own research on the physics of minerals, I have chosen to place microscopic mechanisms at the foundation of our understanding and to build, as far as possible, from this level toward larger scales. This is not the only possible path. One may instead favour effective laws or phenomenological descriptions, which often provide efficient and practical representations of complex systems.

My own preference, however, has been to remain as closely as possible connected to the underlying mechanisms. In my case, this approach was first shaped by transmission electron microscopy, which has long been the central thread of my work, providing direct insight into the structure and behaviour of defects at the microscopic scale. Building on this foundation, multiscale modelling emerged later, notably through the RheoMan project, as a way to extend this understanding across scales and to establish a coherent link between microscopic processes and macroscopic behaviour. More recently, nanomechanical testing, developed within the TimeMan project, has further enriched this framework by offering new ways to probe mechanical properties at scales as close as possible to the underlying mechanisms. Taken together, these approaches reflect a progressive construction, in which different tools have been integrated over time to pursue a consistent, mechanism-based view of mineral physics.

At the same time, recent developments in computational methods, data-driven approaches, and more recently artificial intelligence are opening new avenues for describing complex systems, often with limited reference to their underlying physical

[1] Jean Perrin, Les Atomes (Paris: Félix Alcan, 1913). Perrin was awarded the Nobel Prize in Physics in 1926 for his work on the discontinuous structure of matter, providing decisive experimental evidence for the atomic hypothesis.

[2] "To infer the existence or properties of objects still beyond our knowledge, to explain the complexity of the visible through the simplicity of the invisible — this is the form of intuitive reasoning to which […] we owe atomic theory."

mechanisms. While these approaches can be highly effective, they also raise important questions regarding interpretability and, more fundamentally, the nature of understanding in the physical sciences.

This book reflects a personal answer to that question. It is built on the belief that, despite the difficulties involved, a mechanism-based and multiscale approach remains essential for developing robust and predictive models in mineral physics. It is also, inevitably, the expression of a particular scientific trajectory — one that seeks to identify the elementary processes at the microscopic scale, to quantify their contribution, and to progressively build, from these foundations, a coherent description of material behaviour across scales.

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