THE SELF-POTENTIAL METHOD

Theory and Applications in Environmental Geosciences

The self-potential method is a simple yet innovative process, enabling non-intrusive assessment and imaging of disturbances in electrical currents of conductive subsurface materials by measuring the electrical response at the ground's surface or in boreholes. It has an increasing number of applications, from mapping fluid flow in the subsurface of the Earth to understanding the plumbing systems of geothermal fields, and detecting preferential flow paths in earth dams and embankments.

This book provides the first full overview of the fundamental concepts of this method and its applications in the field. It begins with a historical perspective, provides a full explanation of the fundamental theory, laboratory investigations undertaken, and the inverse problem, and concludes with chapters on seismoelectric coupling and the application of the self-potential method to geohazards, water resources, and hydrothermal systems.

End-of-chapter exercises aid practitioners and students in developing and testing their understanding of the theory and its applications. Additionally, data sets and analytical software are made available online for the reader to put the theory into practice and analyze their own data. This book is a key reference for academic researchers and professionals working in the areas of geophysics, environmental science, hydrogeology, hydrology, environmental engineering, and geotechnical engineering. It will also be valuable reading for related graduate courses.

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André Revil and Abderrahim Jardani
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This book is dedicated to the memory of the Spanish-born physicist Albert Tarantola. Albert's influence on geophysics was profound and immense, especially regarding his work on the inverse problem based on probabilistic foundations and his criticism of the Tikhonov approach (reviewed in this book), still popular nowadays. Albert was a generous man with a strong character and an amazing creativity. We miss him a lot. We invited him in 2008 to give a lecture at the Department of Geophysics of the Colorado School of Mines and this was the lecture that opened our eyes on the use of stochastic approaches, especially Bayesian methods, to self-potential problems as discussed in several chapters of this book.

Albert Tarantola, on his last day at Stanford in 2008. Photo taken by André Journel.

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Foreword

As an environmental scientist who uses geophysical methods to quantify subsurface properties and processes, I recognize the challenges of extracting quantitative information from self-potential data. Although self-potential data are easy to acquire and often provide good qualitative information about subsurface flows and other processes, a quantitative interpretation is often complicated by the myriad of mechanisms that contribute to the signal. Like many others in the community, more than once I have chosen to not collect self-potential data or have abandoned a quantitative interpretation of acquired datasets due to the mechanistic complexity of self-potential signals.

André Revil and Abderrahim Jardani offer a panacea for this common problem through an unparalleled and cutting-edge treatise on the self-potential method, a book that lays a solid foundation for quantitative use of the method to characterize and monitor the Earth's subsurface. The foundation is established through describing the history, physics, and several inversion approaches clearly and comprehensively, and through walking the reader through examples of the use of self-potential data to quantify geotechnical hazards, vadose zone and groundwater processes, and flow in geothermal fields. The book also describes the use or extension of the method to interrogate phenomena not typically explored with self-potential methods, including redox zonation and hydromechanical disturbances associated with fracking. The inclusion of forward and inversion modeling software and a data reduction tutorial will render the book useful for teaching a graduate level course on self-potential. True to André Revil's renaissance style, the book describes many unifying theories and concepts that connect different geophysical signatures and petrophysical properties and that portray a tantalizing vision of future applications using the self-potential method.

The authors have integrated their formidable experience and insights into a valuable book, which marks and propels a quantum leap forward for the self-potential method. It will undoubtedly lead to more acceptance of the self-potential as a quantitative approach and importantly, to new applications that will increase our understanding of subsurface processes and management of precious subsurface resources. This book deserves a central spot on the bookshelves of students, research geophysicists, hydrogeologists, engineers, and professionals.

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Preface

Ten years ago, a good fraction of geophysicists considered passive geophysical methods as having a limited pedigree in comparison to active methods. In the past decade, a breakthrough has occurred in the use of passive seismic methods to image for instance oil and gas reservoir and to monitor dynamic processes (e.g., oil recovery duing water flooding). The same type of revolution has started with the electromagnetic methods, but has lagged behind, limited by the resources of a smaller community. The self-potential method, sometimes nicknamed the ugly duckling of environmental geophysics (Nyquist and Corry, 2002), has been typically used for a broad range of applications, but mostly qualitatively. The self-potential method is, however, one of the oldest of all geophysical methods and is characterized by more complicated (and rich) physics than those used to describe active methods like the d.c. resistivity or seismic methods. It is therefore much more challenging to develop a complete understanding of this method than other classical geophysical methods. The poor understanding of the complex causative sources of self-potential signals has slowed down the quantitative use of this method. The self-potential method is usually not described in geophysicsal textbooks and, when it is described, it is usually with mistakes in the description of the physics or the basic equations. Therefore, we aim to provide here a fundamental description of its electrochemical roots and the quantitative applications of the self-potential method in geophysics and hydrogeophysics, which has been missing to date.

We believe, for the reason mentioned above, that the self-potential method has been underused and its full potential (pun intended) has not been reached. Clearly, a fundamental description of the physics of self-potential signals and the principles of measurements in the field could be used to unleash this method and turn this ugly duckling into a beautiful swan. A few years ago, we also recognized how the self-potential method is similar to another method used in medical imaging: the electroencephalographic (EEG) method. The EEG method has been a breakthrough method in the past decade for mapping brain functions and understanding the dynamics of its electrical activity. The same type of evolution is expected for the self-potential method for a broad range of applications, from exploration geophysics to the production of geothermal systems; from hydrogeophysics to civil and environmental engineering problems. We expect this book will help the community to move forward in this direction. We also invite feedback from readers to help us improve this book in future editions.

We thank also many students and researchers who have directly or indirectly contributed to the present book including Stéphanie Barde-Cabusson, Jean Paul Dupont, Anthony Finizola, Nicolas Florsch, Allan Haas, Becky Hollingshaus, Joyce Hoopes, Scott Ikard, Damien Jougnot, Marios Karaoulis, Vincenzo Lapenna, Niklas Linde, Harry Mahardika, Angela Perrone, Paul Sava, Justin Rittgers, Myriam Schmutz, Magnus Skold, Abdellahi Souied, Bill Woodruff, and Junwei Zhang.

This book is composed of eight chapters that are now briefly discussed.

Chapter 1 introduces the basic concepts of the method. The self-potential method is a passive geophysical method involving the measurement of the electric potential at a set of self-potential stations. The sampled electrical potential can be used to obtain important remote information pertaining to ground water flow, and hydromechanical and geochemical disturbances in the conducting ground. In this chapter, we discuss the principle of the measurements, strategies to map or monitor the self-potential field and the origin of spurious signals and noise. We also discuss the electrical double layer coating the surface of the minerals, which is responsible for an excess of electrical charges (sometimes a deficiency) in the pore water. Finally, we provide a short history of the self-potential method.

The fundamental theory of self-potential signals in porous media is covered in Chapter 2. Our goal is to provide an in-depth understanding of the causes of self-potential signals in deformable porous rocks. We start with an introduction to non-equilibrium linear thermodynamics, which provides the form of the macroscopic constitutive and continuity equations. To gain some knowledge about the material properties, we need to upscale local equations (valid in each phase of a porous composite) to the scale of a representative elementary volume of porous material. These two approaches can be combined to give explicitly the contributions entering into the source current density responsible for self-potential anomalies. The contribution to the self-potential signals associated with the transfer of electrons is investigated separately, as this contribution can be non-linear. This last contribution provides a theoretical basis for the geobattery and biogeobattery models used to localize ore bodies and, more recently, to explain some strong self-potential anomalies observed, under some specific circumstances, over contaminant plumes.

Chapter 3 investigates two types of measurements that can be made in the laboratory to get a better insight on the processes responsible for self-potential anomalies. The first type of measurements concerns core sample measurements. We present electrical conductivity, permeability, and streaming potential measurements and we show how these measurements can be considered into a unified framework of petrophysical properties. Such a unified framework is of paramount importance in considering the natural complementarity of d.c. resistivity, induced polarization and self-potential in solving hydrogeophysical problems. In this chapter, we also discuss a sandbox experiment investigating the geobattery concept and its predictions for ore bodies. We are especially interested in the occurrence of a dipolar anomaly and the role of the redox potential distribution in this behavior.

In Chapter 4, we introduce a finite element formulation to solve the forward self-potential problem associated with ground water flow (primary flow problem). As geophysicists, we are also interested in the inverse problem. We introduce two very distinct ways to invert self-potential data. One approach is to invert the source current density distribution and then to interpret this source current density in terms of relevant parameters (hydraulic head, redox potential, salinity). The second approach is to fully couple the self-potential inverse problem with the physics of the primary flow problem (solving the non-reactive or reactive transport equations and performing the inversion with either deterministic gradient-based or stochastic Bayesian-type approaches).

In Chapter 5, we describe four applications of the self-potential method to geohazard problems including (i) the use of self-potential signals to understand the ground water flow pattern associated with landslides and flank stability, (ii) the detection of sinkholes and cryptosinkholes in karstic environments, (iii) the detection of caves, and (iv) the study of leakages in dams and embankments using salt tracer tests and self-potential monitoring. In each case, we develop a specific approach to interpret self-potential data, and we provide insights regarding the physical mechanisms at play.

In Chapter 6, four additional applications of the self-potential method to hydrogeological problems are described. These applications include (i) pumping tests, (ii) the flow of water in karstic aquifers, (iii) vadose zone hydrogeology, and (iv) the delineation of contaminant plumes associated with a landfills. Each case is illustrated with a different approach, in terms of interpreting the self-potential data. This not only shows the versatility of the applications of the self-potential method in hydrogeology, but also its limitations. The self-potential method should come as a complementary method to in-situ measurements and other (active) geophysical methods.

The self-potential method can also be applied to understand the flow pattern as well as the flow magnitude (to some extent) in hydrothermal and geothermal fields. In Chapter 7, we first propose a stochastic inversion of borehole temperature and surface self-potential data to determine the flow pattern at a depth of several kilometers in a geothermal field. This shows that the self-potential method can be used for deep applications (down to 3 or 4 km). This approach is used to understand the Cerro Prieto geothermal field in Baja California (Mexico), one of the biggest geothermal fields in the world in terms of the production of electrical power. We also develop a gradient-based approach to invert the flow rate of thermal water along faults and we show how this approach can be combined with d.c. resistivity data on two geothermal fields in Colorado and Oregon.

In Chapter 8, we first describe the seismoelectric theory in fully water-saturated conditions. The seismoelectric theory is an extension of the streaming potential theory to the frequency domain, including inertial terms in the momentum conservation equation of the skeleton and pore fluid. It explains how electromagnetic disturbances can be created by the propagation of seismic waves. Then, we provide an extension of this theory to the frequency domain accounting for partial saturation of the water phase. We provide a numerical example related to the water flooding of an oil reservoir and the electrical disturbances associated with the passage of the seismic waves at the oil/water encroachment front. This approach may offer a completely new way to monitor changes in saturation, in both near-surface and deep applications. The passive record of electrical signals can be used to track hydromechanical disturbances in a cement block during the rupture of a seal associated with a fracking experiment. In the last section of this chapter, we briefly show a new approach using beamforming of seismic waves to extract the electrokinetic properties of the point where the seismic field is focused. We believe that this approach could be used to monitor change of saturation in the vadose zone, contaminated aquifers as well to monitor oil and gas reservoirs during their production.