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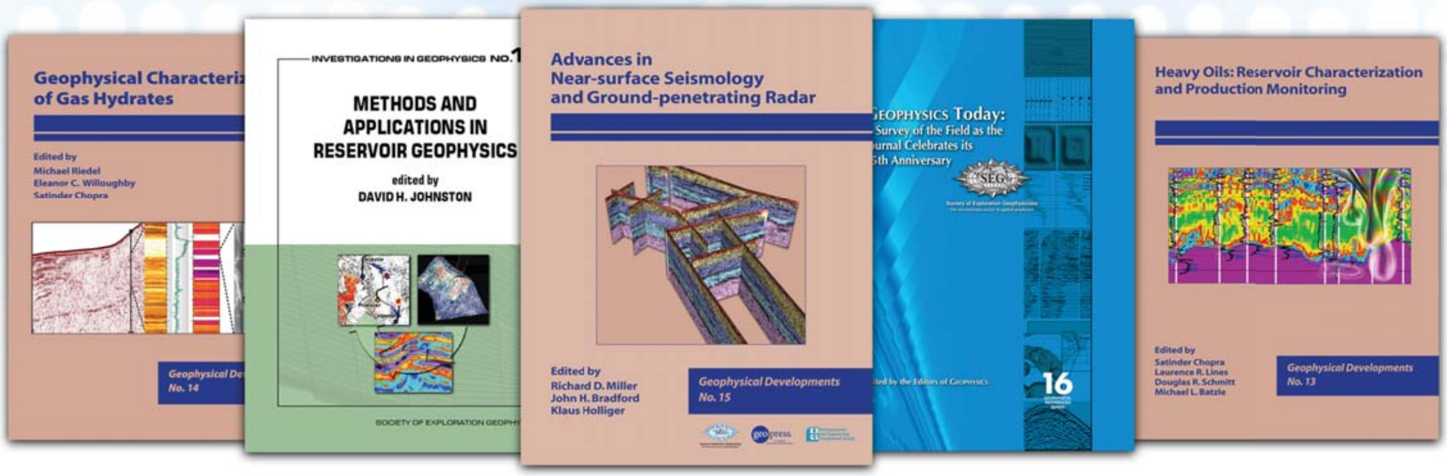

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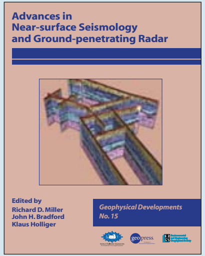

Advances in Near-surface Seismology and Ground-penetrating Radar

SEG eBooks

Edited by Richard D. Miller, John H. Bradford, and Klaus Holliger

Advances in Near-surface Seismology and Ground-penetrating Radar (SEG Geophysical Developments Series No. 15) is a collection of original papers by renowned and respected authors from around the world. Technologies used in the application of near-surface seismology and ground-penetrating radar have seen significant advances in the last several years. Both methods have benefited from new processing tools, increased computer speeds, and an expanded variety of applications. This book, divided into four sections — "Reviews," "Methodology," "Integrative Approaches," and "Case Studies" — captures the most significant cutting-edge issues in active areas of research, unveiling truly pertinent studies that address fundamental applied problems. This collection of manuscripts grew from a core group of papers presented at a postconvention workshop, "Advances in Near-surface Seismology and Ground-penetrating Radar," held during the 2009 SEG Annual Meeting in Houston, Texas. This is the first cooperative publication effort between the near-surface communities of SEG, AGU, and EEGS. It will appeal to a large and diverse audience that includes researchers and practitioners inside and outside the near-surface geophysics community.

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Advances in Near-surface Seismology and Ground-penetrating Radar

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Edited by
Richard D. Miller
John H. Bradford
Klaus Holliger

Rebecca B. Latimer, managing editor

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Society of Exploration Geophysicists
P. O. Box 702740
Tulsa, OK U.S.A. 74170-2740

American Geophysical Union
2000 Florida Avenue N. W.
Washington, D. C., U.S.A. 20009-1277

Environmental and Engineering Geophysical Society
1720 South Bellaire, Suite 110
Denver, Colorado, U.S.A. 80222-4303

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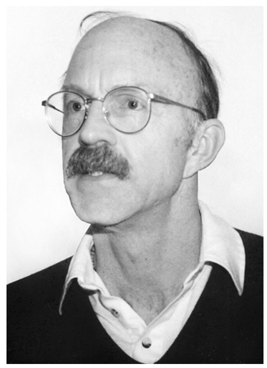

This volume is dedicated to the memory of Roger Adams Young (1943–2009). Roger was an outstanding professor and colleague who committed his career to teaching, mentoring, research, and service. His selflessness, integrity, and kindness made him one of the most valued members of our near-surface community.

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About the Editors

Richard D. Miller has been at Kansas Geological Survey, a research and service division of the University of Kansas, since 1983 and is now a senior scientist and manager of the survey's exploration services section. He also holds a courtesy appointment as associate professor of geology at the University of Kansas. He received a B.A. in physics from Benedictine College in Atchison, Kansas, in 1980, an M.S. in physics with emphasis in geophysics from the University of Kansas in 1983, and a Ph.D. in geophysics from the University of Leoben, Austria, in 2007.

Miller's scientific interests are in shallow high-resolution seismic methods applied to environmental, engineering, energy, groundwater, transportation, and mining problems. From 2005 through 2009, he was a member of SEG's editorial board for THE LEADING EDGE, serving as chairman in 2009. Since 2004, Miller has been guest editor for 12 special sections of *TLE* with a near-surface focus. He has received four research achievement awards, including SEG's Distinguished Achievement Award and Near-surface Geophysics Section Hal Mooney Award, and has written 86 refereed articles.

John H. Bradford joined the academic faculty in the Department of Geosciences at Boise State University (BSU) in Idaho in 2005 and is now an associate professor. He was a research professor at the Center for Geophysical Investigation of the Shallow Subsurface (CGISS) at BSU from 2001 to 2005 and was director of CGISS from 2006 to 2009. He received B.S. degrees in physics and engineering physics from the University of Kansas in 1994. He entered Rice University in Houston, Texas, in 1994, where he held a US EPA STAR graduate fellowship from 1995 through 1997 and received a Ph.D. in geophysics in 1999. From 1995 through 1999, Bradford was a research scientist at the Houston Advanced Research Center, working on topics ranging from utility detection with ground-penetrating radar (GPR) to spectral decomposition for seismic exploration. He was a research scientist at the University of Wyoming from 1999 through 2001.

Bradford has worked in methodology development for near-surface seismic and GPR applications with emphasis on imaging, attenuation, offset-dependent reflectivity, and 3D field methods and analysis. He has had articles published on a diverse array of topics, including hydrocarbon detection, hydrogeophysics, and glaciology, and has organized several workshops and technical sessions at national and international meetings. He served as second vice president of SEG in 2010 and associate editor of GEOPHYSICS from 2005 through 2008 and is associate editor of *Near Surface Geophysics.*

Klaus Holliger has been at the University of Lausanne, Switzerland, since 2005, where he holds a chaired professorship, recently finished a term as vice dean of research, and is now director of the geophysics institute. He received an M.Sc. in 1987 and a Ph.D. in 1990 in geophysics, both from ETH Zurich in Switzerland, and a postgraduate degree in economics in 2000 from the University of London. After extended postdoctoral studies at Rice University in Houston, Texas, he joined ETH's newly founded applied and environmental geophysics group in 1994. He also has worked for shorter periods of time at the U. S. Geological Survey, Imperial College, and the University of Cambridge.

Holliger has been a member of SEG since 1995, was secretary of the Near-surface Geophysics Section from 2003 through 2005, and is now president-elect of the section. He was an associate editor of GEOPHYSICS from 2004 through 2009 and is now editor in chief of the *Journal of Applied Geophysics*. He has broad scientific interests and has worked in a variety of fundamental and applied research domains. He has been a coauthor of more than 100 peer-refereed publications, 18 of which were published in GEOPHYSICS. Holliger's current main research interest is the emerging and inherently interdisciplinary field of hydrogeophysics. He coorganized SEG's first workshop on that topic in 2006 and recently served as guest editor for a hydrogeophysics special issue of *Near Surface Geophysics*.

Acknowledgments

We wish to thank all those contributors who have helped to make this a worthwhile and successful endeavor, specifically the authors and reviewers for their time and conscientious work. Serving as editors of a volume in the SEG Geophysical Developments Series has been an honor and a unique challenge. We believe this book will provide a useful overview of current methodologies and practices in near-surface seismology and ground-penetrating radar. This collection of manuscripts grew from a core group of papers presented at a postconvention workshop, "Advances in Near-surface Seismology and Ground-penetrating Radar," held during the 2009 SEG Annual Meeting in Houston, Texas. It is our hope that this volume will be widely read and will promote further growth and progress in this rapidly evolving and expanding discipline.

We would especially like to thank the publications department of SEG. Under the leadership of publications director Ted Bakamjian, staff members Merrily Sanzalone, Jennifer Cobb, and Rowena Mills led us through each step in the publication process, from invitation of authors to approval of final proofs, all using a new Web-based system. Their tireless efforts, relentless attention to details and schedules, and willingness to keep this book project at the top of their "to-do list" allowed this volume to go from workshop to bindery in less than one year. The authors and volume editors greatly benefited from the professionalism and talents of Merrily, Jennifer, and Rowena. We greatly appreciate the editorial work of Rowena Mills and her team of extremely talented copy editors, consisting of Jennifer Baltz, Anne H. Thomas, Kathryne Pile, Paulette Henderson, and Marilyn Perlberg. We are also grateful to Frances Plants Whitehurst for her assistance with proofreading.

We appreciate the confidence that chairman Yonghe Sun and the SEG Publications Committee placed in our commitment to use SEG's resources wisely and to complete this work in an expeditious and technically sound manner. For a book project like this to be successful, it takes the trust and vision of a seasoned and confident managing editor. We greatly appreciate managing editor Rebecca Latimer for her insight and for the latitude she allowed us.

Thanks to the SEG Executive Committee members during the terms of office of Presidents Larry Lines and Steve Hill, who provided the opportunity to propose this project and the flexibility in the formal SEG book publication process that was necessary to meet our aggressive timelines. This book is unique in its publication schedule and in its objective to bring innovative and fresh workshop topics to the membership quickly and in a refereed format. Larry Lines, in a September 2009 letter to the publications and research committee chairmen and the SEG editor, encouraged this type of workshop-based refereed publication, setting a goal to publish within two years of the workshop. This is the first SEG book to accomplish both these goals.

The papers published in this book underwent the same rigorous peer review as papers published in GEOPHYSICS. At least three experts were selected by one of the technical editors to review each manuscript. The rigorous nature of the review process and the insightful critiques provided by the referees mean each chapter conforms to the high-quality standards that readers have come to expect from refereed SEG publications. We graciously and sincerely thank all reviewers for the hours of volunteer work they provided.

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Arcone, Steven A.

Bano, Maksim

Baron, Ludovic

Buness, Hermann A.

Calderón-Macías, Carlos

Carr, Bradley J.

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The above list should be complete, but if we inadvertently missed someone, please accept our apology.

— Richard D. Miller
John H. Bradford
Klaus Holliger
October 2010

Introduction

Near-surface seismology and ground-penetrating radar (GPR) have enjoyed success and increasing popularity among a wide range of geophysicists, engineers, and hydrologists since their emergence in the latter half of the twentieth century. With the common ground shared by near-surface seismology and GPR, their significant upside potential, and rapid developments in the methods, a book bringing together the most current trends in research and applications of both is fitting and timely. Conceptually, near-surface seismology and GPR are remarkably similar, and they share a range of attributes and compatibilities that provides opportunities to integrate processing and interpretation workflows, which makes them a perfect pair to share pages in a book.

As pointed out by Don Steeples in his foreword to the 2005 book *Near-surface Geophysics* (SEG Investigations in Geophysics Series No. 13, edited by Dwain K. Butler), the first significant refereed collection of papers on near-surface geophysics was published in a 1988 special issue of GEOPHYSICS, followed two years later by the three-volume compilation *Geotechnical and Environmental Geophysics* (SEG Investigations in Geophysics Series No. 5, edited by Stanley H. Ward). Only a few papers published prior to 1975 provided a glimpse of the potential that near-surface seismic characterization possessed (Evison, 1952; Pakiser and Warrick, 1956; Mooney, 1973). Those authors were true pioneers who masterfully demonstrated that potential with a range of well-orchestrated and curiosity-driven research projects.

Although topics related to near-surface seismology had appeared occasionally in the refereed literature prior to 1980, GPR was a virtual unknown at that time. Of the 71 papers in the 1990 book edited by Ward, there was one GPR paper. In contrast, in Butler's 2005 book, four of the 18 papers in the "Applications and Case Studies" section involved GPR, with a major chapter in the "Concepts and Fundamentals" section dedicated solely to GPR. In this context, it is also noteworthy that of the 31 chapters in Butler's book, eight specifically focused on near-surface seismology.

In the last three decades, near-surface geophysics has steadily built up momentum, and in the last decade, it has seen enormous advancements in technologies, applications, and acceptance. If it is fair to use SEG's THE LEADING EDGE (*TLE*) as a gross measuring stick of trends in professional interest, in the seven years between 1996 and 2003, there were three special sections with a near-surface theme, whereas in the seven years since 2003, there have been seven. This increase in near-surface topics in the last half decade or so might well be an indicator of what is in store for the geoscience community in the coming decade. In the 2002 SEG Annual Report, then SEG president Walter Lynn discussed the likely diversification of the society's members in the years to come, stating that "exploration geophysics is not just a tool for the petroleum and mining industry. . . ." Recent growth and diversification of SEG are nowhere more evident than at the 2010 annual meeting in Denver, Colorado, at which about 10% of the oral sessions were proposed by or affiliated with SEG's Near-surface Geophysics Section.

With growth in numbers and professional emphasis have come sections, focus groups, and even professional societies specifically promoting near-surface geophysics. The emergence of near-surface geophysics groups, beginning in the late 1990s and extending into the early twenty-first century, has fueled a diversity of opportunities for professional collaborations. A range of workshops and shared publications has been the fruit of collaborative efforts. The near-surface community continues to extend and develop methods and approaches necessary to satisfy increasing demands in some of the socioeconomically pertinent disciplines such as civil and environmental engineering and hydrology. This book represents the first formal cooperative effort undertaken by the near-surface communities of the Society of Exploration Geophysicists, the American Geophysical Union, and the Environmental and Engineering Geophysical Society.

At the 2009 SEG annual meeting in Houston, Texas, representatives from three of the major near-surface groups organized an after-conference workshop titled "Advances in Near-surface Seismology and Ground-penetrating Radar." This workshop was designed to capture both new and innovative methodologies being developed and implemented by leading researchers from around the world. It was also a goal of the workshop to highlight studies that show the applicability of integrating various seismic and GPR methods to enhance near-surface characterizations. Technologies used in the application of near-surface seismology and GPR have benefited from new processing tools, increased computer speeds, and an expanded variety of applications. Many shallow-seismic projects now incorporate analysis results from different parts of the seismic wavefield, allowing for greater redundancy and confidence in interpretations without increased acquisition costs. More information is being extracted from GPR data by adapting and using the wide range of analysis techniques developed for seismic data in concert with new tools specific to high-frequency electromagnetic wave analysis.

Leading investigators were invited to present research at the workshop and submit papers for consideration to be published in this book. To diversify the book as well as to capture many of the most current and significant research developments in near-surface seismic and GPR, more than 60 authors were invited to submit manuscripts for inclusion in this book. From those 60, the cream of the crop appears in the 29 chapters of this book. The book is divided into four principal areas: "Reviews," "Methodology," "Integrative Approaches," and "Case Studies." History will be the judge in determining which of these manuscripts will become landmark works cited as classics for many years to come.

Reviews

Establishing a vision for future developments requires a thorough understanding of the evolutionary path that a technique or method has taken to reach its current state. The review papers in the first section of this book provide that kind of framework and set the stage for papers in later sections that describe innovative and creative advancements in the use of seismic or GPR. As a good starting point in the review of past developments, the **Linde and Doetsch** paper provides an excellent example of joint inversion of GPR and seismic data and demonstrates improvements in characterization potential using this multimethod approach.

Without a doubt, exploitation of surface waves has been one of the fastest-growing areas in near-surface seismology in the last decade. **Xia and Miller** present a review of the estimation of near-surface shear-wave velocities and quality factors through the inversion of high-frequency Rayleigh waves, a technique now commonly referred to as multichannel analysis of surface waves (MASW). Several real-world examples demonstrate the applicability of inverting high-frequency Rayleigh waves as part of routine MASW applications. This chapter is rounded off by an algorithm for assessing the quality and reliability of MASW inversion results based on the trade-off between model resolution and covariance.

Complementing the Xia and Miller paper is a second surface-wave review paper, by **Xu et al.,** which describes some of the significant and creative developments in China in the last decade. The theory is well developed, and the examples are equally compelling.

With another look back, **Socco et al.** discuss optimal acquisition strategies for obtaining multipurpose seismic data sets and assess the potential improvements that can be achieved by a constrained or joint inversion of various types of seismic data. These concepts are illustrated in several real-world cases extracted from recent projects. With the surge in the use of surface waves in near-surface seismology, it is not surprising that three of the four review papers touch on that part the wavefield.

Methodology

The past 10 years have seen an explosion in methodology development for near-surface seismic and GPR applications, and new developments continue to accelerate. In contrast with the early days of near-surface geophysics, relative maturity of hardware design and field methodologies has allowed researchers to focus increasingly on data processing and analysis algorithms that enable extraction of detailed quantitative information. It is interesting to note that although many analysis methodologies in the past were borrowed from the oil industry, near-surface researchers are now at the forefront of imaging and inversion, developing tools to solve problems unique to the shallow subsurface.

The papers in the methodology section capture many of these new developments. For example, **Irving et al.** present an effective method for extracting geostatistical structure based on 2D autocorrelation of reflection images.

An innovative approach is taken by **van der Kruk et al.** as they move closer to true-amplitude migration of GPR data and describe an approach that accounts for both the vector nature of electromagnetic wave propagation and the strong directionality of GPR antenna radiation patterns.

The paper by **Gloaguen et al.** develops a multiscale conditional stochastic simulation approach based on the wavelet transform. The proposed method is tested on synthetic crosshole GPR and is applied to a corresponding field data set. Results indicate that the method is capable of reproducing the larger-scale structural grain imaged by the geophysical data and to stochastically "fill in" the smaller-scale texture based on complementary information and/or constraints.

Looking toward a wide range of applications, **Ghose** presents a data-driven method that allows estimations of the in situ horizontal stress in the subsurface and monitoring of its temporal evolution based on fixed-array seismic shear-wave measurements. The corresponding model is validated on data from extensive laboratory experiments, which indicate that predictions based on the shear-wave seismic data are remarkably accurate.

The work by **Baron and Holliger** represents a significant contribution in our quest for a better understanding of the rock physics of unconsolidated sediments. In their paper, they attempt to apply Biot poroelasticity theory to shallow sediments, exploring the possibility of estimating the permeability of saturated surficial alluvial sediments based on the poroelastic interpretation of the velocity dispersion and frequency-dependent attenuation of such broadband sonic-log data.

Using an unconventional approach to extract more information from GPR data, **Haney et al.** analyze the dispersive characteristics of guided GPR waves and interpret the transition from a stream channel to a peat layer along the acquisition line. They find that guided waves capture shallow structure near a stream channel that is not imaged accurately in the reflection profile, thus demonstrating the utility of guided GPR waves for providing information on shallow structure that cannot be obtained from GPR reflection profiling.

Looking at the improvements in image accuracy when all components of the surface wave are correctly identified and included in the analysis, **Calderón-Macías and Luke** analyze the sensitivity of Rayleigh-phase velocity inversion in some specific surficial scenarios and explore the potential of adding higher modes to the analysis of fundamental mode data.

In a continuing effort to identify and classify subsurface anomalies, **Sloan et al.** explore the potential of three seismic methods for the detection of voids in the subsurface: (1) Diffracted body waves are used to identify and locate man-made tunnels in multiple geologic settings, (2) variations in shear-wave reflection velocities are shown to correlate to changes in stress over known void locations, and (3) backscattered surface waves are shown to correlate with a known void location. For all methods, field data correlate well with synthetic data.

Vertical resolution continues to be a research focus**. Deparis and Garambois** develop a dispersive amplitude-and-phase-versus-offset (DAPVA) approach for GPR reflection data to quantitatively analyze reflections from thin beds. Tests on synthetic and real data indicate that this approach carries significant potential for constraining the petrophysical properties of thin beds in general and the filling of fractures in particular.

Introducing a controversial approach to first-arrival analysis, **Palmer** proposes to use seismic attributes as a means to reduce the nonuniqueness of refraction methods. His work incorporates seismic attributes with the generalized reciprocal method and refraction convolution. This paper undoubtedly will stimulate discussion and a look to the future of refraction analysis.

An innovative application of the GPR method detailed in the paper by **Slob and Lambot** demonstrates how frequency-domain analysis of the surface reflection, recorded from an off-ground GPR system, can improve estimates of surface soil permittivity and electric conductivity in contrast to the time-domain method.

In a unique look at shear polarized surface waves, **Michaels and Gottumukkula** present a theory for viscoelastic Love waves by relating viscosity to permeability. The authors explore the method's potential for constraining the permeability of surficial soil and rock layers, which provides several recommendations with regard to the optimal design of corresponding seismic surveys.

Integrative Approaches

Integrating data from different geophysical methods as a means of reducing nonuniqueness has long been recognized as an important step in the development of geophysical tools. However, methods for effectively implementing this concept have remained elusive, with problems such as differences in volume scaling, errors related to petrophysical assumptions among methods, and computational limitations proving difficult to solve. Researchers have recently made strides in data integration, and the papers in this section provide some exciting examples of what is being done.

In the study of a fault-controlled hydrothermal reservoir, **Musmann and Buness** show how high-resolution seismic reflection can be integrated with conventional industry-scale images to significantly improve the understanding of fault geometry in the near surface.

To assess the threat of landslides, both onshore and within a fjord, **Polom et al.** apply a high-resolution multichannel SH-wave seismic-reflection land survey complemented by a dense network of high-resolution single-channel marine seismic profiles over the deltaic sediments in a fjord to characterize in situ soil conditions. SH-wave seismic reflection provides a nearly direct proxy for in situ soil stiffness, a key geotechnical parameter.

Moving closer to full integration of seismic and GPR, **Bradford** uses 3D GPR and seismic-reflection data to image a shallow aquifer. He demonstrates that through an integrative interpretation approach that accounts for the complementary character of these data, he can provide a reliable 3D image of the major hydrostratigraphic units.

Looking to improve the selection of initial models used for first-arrival inversion, **Ivanov et al.** study the problem of nonuniqueness in refraction traveltime inversion and describe a method which uses the surface-wave-derived shear-wave velocity model to constrain the P-wave refraction problem.

Case Studies

A critical step in the maturation of a new methodology is its demonstration through careful field study. The papers in this section are just such examples of well-illustrated case studies highlighting the value of an approach. The need to characterize areas with the potential for ground amplification makes the work of **Hunter et al.** significant to zoning and building codes in earthquake-prone areas. The authors first describe downhole and surface methods for measuring shear-wave velocities and then show how those measurements were used to assess seismic hazards in two Canadian cities.

A follow-up study by **Ogunsuyi and Schmitt** demonstrates how additional information can be extracted from conventionally processed data and how important it is to match stacked events on common-midpoint sections with associated reflections on shot gathers at times less than 50 ms. Also significant to many near-surface seismologists is the demonstrated need for an extremely accurate velocity function for effective prestack depth migration and how difficult it is to obtain those accurate velocities. New and previously undetectable features were interpreted on the reprocessed sections presented in this paper.

Stochastic modeling conditioned by crosshole GPR and lithologic data from boreholes allowed **Nielsen et al.** to estimate the fine-scale lithologic heterogeneity of rock from the Chalk Group. The results indicate that with this conditioning, the pursued stochastic simulation approach is capable of modeling the distribution of the pertinent lithologies and produces realistic models of Chalk Group heterogeneity.

The paper by **Renalier et al.** demonstrates the potential for characterizing and monitoring unstable clay slopes based on various active and passive shear-wave measurement techniques. The shear-wave velocity of clayey materials is very sensitive to mechanical disturbances associated with landslide movements and shows a pronounced negative correlation with GPS deformation measurements in such areas.

Time-lapse monitoring of soil moisture using surface seismic methods is a viable approach but has seen little application thus far. **Gaines et al.** use a series of P-wave refraction profiles to monitor variations in a perched water body lying within 4 m of the surface.

In areas with a low GPR velocity underlain by a higher-velocity material, a critically refracted GPR phase can lead to errors in depth estimates when the critical distance for refractions is less than the fixed transmitter-receiver offset. **Hermance et al.** describe a simple composite moveout correction that can correct the problem. They illustrate their approach for a stratified glacial drift site in southeastern New England.

Use of the S-transform on GPR data is not unique, but the study described by **Elwaseif et al.** is a compelling application of the approach. The authors demonstrate the potential of GPR data to locate water-filled fractures down to one-quarter the dominant wavelength and to delineate possible localized transport passages for moisture between fractures via capillary effects.

With the SPAC method first described by Aki's 1957 paper, **Stephenson and Odum** provide a modern look at an application of this ambient noise-analysis method at a small basin scale in the Salt Lake City, Utah, area. With the relationship between shear-wave velocity and amplification, the demonstrated compatibility of the SPAC method with more traditional borehole methods makes it a viable alternative for developing 1D V_S functions.

Coincident MASW and H/V studies allow **Kanlı** to improve the accuracy of the shear-wave velocity function from the near-surface interval down to bedrock. This case study describes an inversion routine that uses a genetic algorithm. Although each component of this study has been described and discussed by other authors, the focus on integration is a clear trend in near-surface seismology and GPR.

It is clear from these summaries that the breadth and depth of this collection of papers is exceptional, touching on a full gamut of current research areas. Near-surface seismologists are making significant progress at unraveling the full wavefield and exploiting all aspects that provide insights into subsurface properties. Likewise, GPR researchers are finding new and innovative ways of using electromagnetic waves to measure electrical properties and relating those to hydrologic and geologic properties. A clear underpinning of many papers in this book is the incorporation of advanced modeling and inversions methods as tools for more accurate and complete characterizations of the subsurface.

Our intent is that the papers in this book are sufficiently forward looking that the volume will serve as a reference for researchers in the next decade and a valuable supplement for graduate or advanced undergraduate courses in near-surface seismology, GPR, or general near-surface geophysics. The credit for making this book project possible and successful goes to the individual contributors. Finally, it should be noted that the origin of this book project (a workshop-based refereed publication) is unique for SEG publications. We intend it to be the first in a series of books highlighting the broad spectrum of techniques, tools, and applications that comprises near-surface geophysics.

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