

METHODS IN GEOCHEMISTRY  
AND GEOPHYSICS

---

EXPLORATION WITH DEEP  
TRANSIENT ELECTROMAGNETICS

K.-M. STRACK



elsevier

# EXPLORATION WITH DEEP TRANSIENT ELECTROMAGNETICS

K.-M. STRACK

*Western Atlas International, Atlas Wireline Services, P.O. Box 1407,  
Houston, TX 77251, USA*

formerly

*HarbourDom Consulting, Alvenslebenstr. 15, 5000 Köln 1, Germany*

and

*Universität zu Köln, Institut für Geophysik und Meteorologie, Albertus  
Magnus Platz, 5000 Köln 41, Germany*



ELSEVIER

Amsterdam – London – New York – Tokyo 1992

ELSEVIER SCIENCE PUBLISHERS B.V.  
Sara Burgerhartstraat 25  
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Library of Congress Cataloging-in-Publication Data

Strack, Kurt-Martin, 1957-

Exploration with deep transient electromagnetics / K.-M. Strack.

p. cm. -- (Methods in geochemistry and geophysics ; 30)

Includes bibliographical references and index.

ISBN 0-444-89541-8

1. Electric prospecting. 2. Electric prospecting--Case studies.  
3. Magnetic prospecting. 4. Magnetic prospecting--Case studies.  
5. Electromagnetism. 6. Electromagnetism--Case studies. I. Title.

II. Series.

TN269.S76 1992

622'.154--dc20

92-12266

CIP

ISBN 0-444-89541-8

© 1992 Elsevier Science Publishers B.V., All rights reserved

No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of the publisher, Elsevier Science Publishers B.V., Copyright & Permissions Department, P.O. Box 521, 1000 AM Amsterdam, The Netherlands.

Special regulations for readers in the U.S.A. - This publication has been registered with the Copyright Clearance Center Inc. (CCC), Salem, Massachusetts. Information can be obtained from the CCC about conditions under which photocopies of parts of this publication may be made in the U.S.A. All other copyright questions, including photocopying outside of the USA, should be referred to the publisher.

No responsibility is assumed by the Publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein.

This book is printed on acid-free paper.

Printed in The Netherlands

*I am dedicating this book to those  
who have given me their infinite love  
while I was working on this manuscript:*

*Heather, Ian and Gurumayi*

*Only your support has allowed to  
accomplish this huge task.*

## PREFACE

This book has a story. The author's first version was used for lectures at the University of Cologne and as a training program for foreign scientists. The second version was written as part of a project report and the third version as lecture notes for the lecture series "New Methods in Electromagnetic Exploration" held in 1989/90.

This book is history. It is a milestone in the history of electromagnetic geophysics, or to be precise, of quantitative electromagnetic exploration methods.

It all started 50 years ago with the telluric method. After that came Magnetotellurics in 1953, introduced by Cagniard, Tikhonov and Rikitake. Thanks to subsequent advances in technology, this method proved its effectiveness for crustal studies, as well as a number of specific situations encountered in hydrocarbon exploration.

Because reliance on natural signals does have some drawbacks, a great deal of effort was made later to develop controlled source electromagnetics. We are all indebted to the work carried out in the former USSR in this field in the last thirty years. A whole new appendix devoted to a Russian bibliography would have to be added to the book to give these pioneers the place they deserve in history.

In the beginning, there were two competing families of methods: frequency and time domain measurements. Time Domain Electromagnetics (TDEM) or Transient Electromagnetics (TEM) have won broad acceptance for a wide range of applications from shallow exploration to deep crustal studies. LOTEM, the method taken in this book as a reference, is now gaining recognition among geophysicists. This is the result of a natural selection process. Since LOTEM combines the advantages of TEM methods, the measurement of a broadband secondary field in the absence of a source signal and the advantage of DC soundings, it resolves resistive markers.

Kurt Strack's involvement in TEM started in the USA, continued in Australia, until he finally settled in Germany. His contributions have been decisive, ranging from the introduction of modern signal processing algorithms to the development of multichannel equipment, and resulted in Cologne becoming a focal point for a number of international experts, particularly for modeling. Last but not least, he managed, after overcoming formidable difficulties, to organize demonstrative surveys on four continents.

This book is going to influence history.

With its nine chapters, seven appendices, exercises and floppy disk, we consider it to be the most comprehensive textbook currently available. So, you want to become an expert in deep transient electromagnetics? Well, just study and understand this book. It will doubtless influence present and future specialists in TEM, whether they wish to concentrate on instrument design, data processing and interpretation or hydrocarbon discovery.

Exploration managers and Chief Geophysicists should read at least chapter 6 to 9 in which feasibility studies and case histories are covered. A particularly important topic is the integration of seismic and LOTEM for studies of lithology, porosity and fluid content.

Chapter 1 to 5 are for TEM specialists in universities and oil companies and, of course, for students who will be delighted to read a book which offers a rare combination of depth, thoroughness, and clarity.

Both of us have worked for many years for a contracting company which, since the days of C. Schlumberger, S. Stefanescu, L. Cagniard, V. Baranov, and G. Kunetz, has taken pride in offering a comprehensive range of geophysical services including electromagnetics.

We are particularly pleased today to have this opportunity to tell all potential readers, who not only want to understand deep transient electromagnetic soundings but also to discover how they fit into a well designed exploration program: "This is THE BOOK for you!"

Gildas Omnes and Pierre Andrieux

Massy, France, February 10th, 1992

## TABLE OF CONTENTS

PREFACE .....	vii
TABLE OF CONTENTS .....	viii
ACKNOWLEDGEMENTS .....	xi
SUMMARY .....	xiv
<b>Chapter 1: Introduction</b> .....	<b>1</b>
THE ROLE OF ELECTROMAGNETIC METHODS IN EXPLORATION .....	2
HISTORICAL DEVELOPMENT OF LOTEM .....	5
ELECTRICAL CONDUCTIVITY / RESISTIVITY IN EXPLORATION .....	9
SUMMARY CHAPTER 1 .....	17
PROBLEMS CHAPTER 1 .....	18
<b>Chapter 2: Basic Theoretical Background</b> .....	<b>21</b>
PHYSICAL PRINCIPLES .....	21
THEORETICAL BACKGROUND .....	24
APPARENT RESISTIVITY .....	26
ALL TIME APPARENT RESISTIVITY .....	32
IMAGE PRESENTATION OF THE DATA .....	35
SUMMARY CHAPTER 2 .....	45
PROBLEMS CHAPTER 2 .....	46
<b>Chapter 3: Distortions of the Signal and their Compensation.</b> ....	<b>47</b>
THE FIELD PROBLEM .....	47
DECONVOLUTION OF THE SYSTEM RESPONSE .....	49
RECURSIVE DIGITAL FILTERS .....	52
SELECTIVE STACKING METHODS .....	58
CALIBRATION FACTOR .....	62
PRESTACK AND POSTSTACK PROCESSING .....	68
SUMMARY CHAPTER 3 .....	70
PROBLEMS CHAPTER 3 .....	71
<b>Chapter 4: Data Interpretation</b> .....	<b>73</b>
ONE-DIMENSIONAL INVERSION .....	73
<i>Resolution Analysis</i> .....	81
<i>Joint Inversion</i> .....	83
<i>Profile Inversion</i> .....	91
<i>Occam Inversion</i> .....	99
INTERPRETATION OF DISTORTED TRANSIENTS (REVERSALS) .....	102
<i>Numerical Simulation of Reversals</i> .....	109
THREE-DIMENSIONAL MODELING .....	116
<i>Simulations of Transmitter Overprints</i> .....	117
<i>Comparison of Different 3-D Modeling Programs</i> .....	122
SUMMARY CHAPTER 4 .....	124
PROBLEMS CHAPTER 4 .....	126

<b>Chapter 5: The Field System and Field Procedures</b> .....	127
SYSTEM CONCEPTS .....	128
<i>Transmitter Systems</i> .....	133
<i>Synchronization between Transmitter and Receiver</i> .....	135
<i>Advantages of using Multichannel systems</i> .....	138
<i>Mobile Processing Systems</i> .....	150
FIELD PROCEDURES .....	151
<i>Transmitter Electrode Preparation</i> .....	151
<i>Initial Transmitter Check Out</i> .....	153
<i>Routine Daily Synchronization Check</i> .....	153
<i>Measuring the System Response</i> .....	154
<i>General Considerations</i> .....	156
SURVEY TECHNIQUES .....	158
<i>Single Site Field Procedures</i> .....	158
<i>Multichannel Field Procedures</i> .....	160
<i>Local Noise Compensation Technique</i> .....	161
SUMMARY CHAPTER 5 .....	171
PROBLEMS CHAPTER 5 .....	172
<b>Chapter 6: Survey Feasibility Studies</b> .....	173
SURVEY DESIGN BASED ON WELL LOGS .....	173
RESOLVING A DEEP CARBONATE UNIT .....	182
HIGH RESOLUTION FEASIBILITY STUDY .....	184
FEASIBILITY STUDY OVER A TWO-DIMENSIONAL STRUCTURE .....	187
SUMMARY CHAPTER 6 .....	190
PROBLEMS CHAPTER 6 .....	191
<b>Chapter 7: General Case Histories</b> .....	193
FIELD SURVEY NORTH OF THE RUHR DISTRICT, FRG .....	193
GEOLOGICAL CALIBRATION OF THE TECHNIQUE IN THE DENVER - JULESBURG BASIN, USA .....	205
FIRST FIELD TESTS IN AUSTRALIA (SYDNEY BASIN) .....	208
3-D INTERPRETATION CASE HISTORY MÜNSTERLAND BASIN, FRG .....	215
<i>Results of Thin-Sheet Modeling</i> .....	219
<i>Results of Integral Equation Modeling</i> .....	220
<i>Results of SLDM Modeling</i> .....	222
<i>Discussion of 3-D Interpretation</i> .....	224
SUMMARY CHAPTER 7 .....	225
PROBLEMS CHAPTER 7 .....	226
<b>Chapter 8:</b>	
<b>Case Histories: Resolving Resistive Layers with LOTEM</b> .....	227
EXTENSION OF THE PHYSICAL CONCEPT TO RESISTIVE LAYERS .....	228
EUROPEAN CASE HISTORY .....	229
CANNING BASIN, AUSTRALIA, CASE HISTORY .....	235
TAI XING AREA, PRC, CASE HISTORY .....	240
SUMMARY CHAPTER 8 .....	246
PROBLEMS CHAPTER 8 .....	246
<b>Chapter 9: Case Histories: Deep Crustal Applications</b> .....	247
HISTORICAL CASE HISTORIES .....	247
THE FIRST DEMONSTRATION FOR DEEP CRUSTAL APPLICATIONS IN FRG .....	252

BLACK FOREST SURVEY .....	256
URACH GEOTHERMAL AREA .....	264
TEST SURVEY OVER THE KAAPVAAL CRATON, R.S.A. ....	268
TEST MEASUREMENTS IN CHINA FOR THE APPLICATION OF LOTEM FOR EARTHQUAKE PREDICTION .....	274
<i>Data Base of the Tangshan Area</i> .....	275
<i>The LOTEM Survey</i> .....	277
<i>Discussion of the Results</i> .....	279
DISCUSSIONS .....	281
SUMMARY CHAPTER 9 .....	283
PROBLEMS CHAPTER 9 .....	284
<b>Appendix 1 – Derivations</b> .....	285
PROOF OF THE ITERATIVE DECONVOLUTION .....	285
SINGULAR VALUE DECOMPOSITION. ....	287
SOLUTION OF MAXWELL'S EQUATIONS USING SCALAR POTENTIALS. ....	288
<b>Appendix 2 – Data Format Standards</b> .....	297
INTRODUCTION .....	297
FILE FORMATS .....	298
<i>Format of a LOPS Data File</i> .....	298
<i>Format of A LOPS Stacked Data File</i> .....	298
FILE HEADER .....	300
TRACE HEADER STRUCTURE .....	304
<b>Appendix 3 – Useful Information</b> .....	307
GLOSSARY .....	307
OPERATOR'S LOG – SINGLE SITE RECEIVER SYSTEM .....	311
CLOCK DRIFT MEASUREMENT LOG .....	312
LOTEM TRANSMITTER RECORD SHEET .....	313
INVERSION STATISTICS .....	314
<b>Appendix 4 – Documentation of the Forward Modeling Program MODALL</b> .....	317
SOFTWARE INSTALLATION .....	317
DESCRIPTION OF THE MENUS .....	318
EXAMPLES .....	321
<b>Appendix 5 – List of Figures, Tables, Symbols and References</b> .....	325
LIST OF FIGURES .....	325
LIST OF TABLES .....	338
CONVENTIONS AND LIST OF SYMBOLS .....	339
REFERENCES .....	340
<b>Appendix 6– Subject Index</b> .....	349
<b>Appendix 7– Color Figures</b> .....	367
<b>INSERT: FLOPPY DISKETTE with SOFTWARE</b>	



## ACKNOWLEDGEMENTS

I thank everybody, who made it possible for me to write this book. In particular, I would like to thank the members of the LOTEM research group at the University of Cologne for their active contribution. In addition to those directly involved in my work, I would like to thank H. Petry for his help in compiling and writing the initial material about the inversion and forward modeling section. H.N. Eilenz helped a great deal with the initial start up of the LOTEM project. Tilman Hanstein, who was one of the scientists of the "first hour", contributed to many parts to these notes. He spent many uncountable hours in order to find the optimum procedures to solve a problem. Greg Newman helped tremendously by contributing his 3-D integral equation program to the modeling tools. Peter Weidelt contributed a new generation of a three-dimensional plate program and simulated with it some reversals. Andreas Hördt contributed significantly to the corrections and clarity of the manuscript as well as significantly to the inversion chapter. Gülcin Karlik developed the source imaging for LOTEM data and calculated most of the imaging figures. V. Druskin, L. Knizhnerman, and P. Weidelt helped us to integrate 3-D modeling into the interpretation of real data. A. Hördt spent countless hours to implement, improve and apply their programs to our field data. M. Eckard, C. L. Le Roux, J.L. Seara, and M.D. Watts read carefully parts of this manuscript and provided helpful comments. Last but not least, I would like to acknowledge Peter Wolfgram's continuous support at all levels throughout this research and his constructive comments and corrections. Many unnamed research assistants, graduate students, and colleagues have contributed to the results presented here. To all of them very special thanks.

Especially, I would like to thank my teachers at the Colorado School of Mines, A. Kaufman, G.V. Keller and C.H. Stoyer. Prof. Kaufman was always very concerned that I would not study hard enough and could embarrass him when going back to Europe. He thus generated the ordeal of countless oral exams for me. I never found out whether the reason for this were his expectations or that I fell asleep once during his lecture. Prof. Keller always complained about me being a difficult student because he felt I was telling him what to do. Nevertheless, he gave me many outstanding opportunities which clearly mark my professional career. Prof. Stoyer spent many hours with me building systems supported by plywood and stubbies. Most of the time we succeeded in fastening the different pieces together which left us with a very "tight" friendship.

At "home", I am grateful for the support of Profs. A. Ebel and F.M. Neubauer. Prof. Ebel did not only help me get "out of" Cologne and to the US, but was instrumental in bringing me back from Australia. Prof. Neubauer provided from the first day on a significant amount of support far beyond his continuous moral support. Most

important, he gave me the free 'room' required to carry out the work leading to this book.

Parts of this research were supported by the European Community (contract TH/0159/85-DE), the German Ministry for Science and Technology (03E6360A and 0326550B), the NRW (IVB4-10Y-003-86), the German Science Foundation (DFG) and many other sources. Some of the 3-D modeling and interpretation was funded under German Science Foundation Contract Str. 323 / 1-1.

Integrated GeoSciences Inc. of Golden, Colorado kindly made their work from the Milford Valley in Utah available to the public.

The final prototype (series 1) TEAMEX system was funded by the State of NRW to enable us to carry out technology transfer projects. Prof. Rüter provided the framework to make the plan of the TEAMEX part of reality. W. Martin, alias "the TEAMEX CPU", was very open for all the extra wishes we had.

Pacific Oil & Gas Pty. Limited, Australia, kindly provided the background information for one of the feasibility studies. Dr. Takasugi of the Geothermal Energy research and Development Co., Ltd. kindly provided the the background information for the feasibility study for a target in Japan.

The case history in the Northern part of the Ruhr district was partially supported by the Ministry for Science and Research of the state of NRW and a donation by the television station WDR. A. Stephan conducted most of the research in course of his M. Sc. thesis and helped tremendously to make the survey a success.

Permission of publication and the initiative for the measurements in the Denver-Julesburg basin was given by N. Harthill, formerly Group Seven Inc., who also helped me focus my interest on the LOTEM technique.

The test survey in Australia was funded by a Macquarie University Research grant and BHP exploration. I also acknowledge the support given to the Australian case history in the Canning Basin by ESSO Australia and the National Energy Research, Development and Demonstration Committee (NERDDC, Australia, contract 683-833453). The research was carried out by K. Vozoff with the support of K. McAlister, K. LeBrocq, D. Moss, D. Pridmore and M. Zile. Hardware support in Australia was given by Zonge Engineering and Research Corporation.

The survey near the Tai Xing area was carried out within the German LOTEM Demonstration Project in China and India. Crew management was done by T. Speth and the interpretation by P. Lenson, J.L. Seara and P.A. Wolfgram. Apart from all other participants Zhang Zhi Jie of the Petroleum Bureau in Nanjing provided significant input to his survey. To all of them and all the unnamed help in the project a very special thanks.

The application to deep crustal geophysics was initiated and supported by Profs. V. Haak, F.M. Neubauer, and H. Wilhelm. E. Lüschen was a "key colleague" throughout the tests. His guidance proved to be essential for the success during the Black Forest survey. The extension of the LOTEM system for crustal applications was only possible through the help of C. Kalle in rewriting the entire assembler code of the acquisition system.

The survey over the Kaapval craton was funded by the South African National Geophysics and Geoscience Programme. C.L. Le Roux and T. Hanstein made a lot of sacrifices to get the data collected. J.H. de Beer supported the LOTEM work in South Africa tremendously from the very beginning until nowadays. Many unnamed CSIR staff members help carrying out the survey. A very special thanks to all of them.

The work in Tangshan area in China was supported by Prof. Liu Guodong of the State Seismological Bureau in Beijing. Field crew managing was done by T. Speth who very smoothly steered the crew through lots of logistical troubles. A. Stephan and J. Rossow carried out the processing and preliminary interpretation. Geometra GmbH provided logistical support.

I am grateful for the financial support given for the preparation of this book by HarbourDom Consulting GmbH.

Many coworkers and friends contributed through corrections and invested a significant amount of time. They are:

R. Birken	M. Eckard	O.G. Engels	T. Hanstein
A. Hördt	M. Jegen	G. Karlik	A. Krämer
T. Lal	J.L. Seara	R.J. Smith	W. Stiefelhagen
C.H. Stoyer	K. Vozoff	P.A. Wolfgram	M.D. Watts

M. Heinert, E. Teneta and M. Eckard typed most of the manuscript and fought the uncertainties of the DTP system. J. Schloßmacher patiently took care of the plants and helped significantly with the administrative part (except for making coffee).

Finally, I would like to thank my teacher, friend, colleague and supporter K. Vozoff who not only brought me onto the path of doing more research with LOTEM, but also morally supported me throughout the entire work.

## SUMMARY

Over the past few decades electromagnetic (EM) techniques have taken an increasing importance for the exploration of hydrocarbons and geothermal resources as well as deep crustal studies. The reason lies in the response to different physical rock properties, namely electrical resistivity, in comparison to the elastic properties for seismic methods. Among the electromagnetic techniques the deep transient electromagnetic technique has seen an increasing interest because of the possibility of overcoming typical electromagnetic noise problems as well as obtaining higher resolution with better transmitter control. Although many excellent theoretical books exist on electromagnetics and some applied books on individual electromagnetic methods, there is no coherent description of deep transient electromagnetics which allows the geophysicist to learn about the technique from the beginning of instrument design to the final interpretation.

This book is trying to fill that gap by summarizing many man years of research. It is directed towards a broad audience: the *research geophysicist* who is going to design his own transient electromagnetic field system; the *student* who is trying to learn about the theoretical background and its direct relation to real practical application; the *exploration geophysicist* who will have to make the survey design, cost evaluation and interpretation. This review will help him to refresh some of the background material. All chapters have a very strong relation to real case histories. Problems are included to help deepen the understanding beyond the content of this book and test programs to demonstrate the application. A combination of all should allow the newcomer to deep transient electromagnetics to reach very quickly state-of-the-art level.

Chapter one contains a general introductory section which explains where deep transient electromagnetics is placed in geophysical exploration. It also explains the background of rock resistivity often used as a priori information in the interpretation of electromagnetic data. The second chapter gives a short review of the basic physical principles in order to allow the practicing geophysicist to relate to possible problems in interpretation. The material is restricted to the basic needs for data interpretation; more detailed derivations are given in the appendix 1.

The difficult problem in acquiring and processing electromagnetic data is the improvement of the signal-to-noise ratio, which is treated in chapter three. Using the information in this chapter, the reader should be able to handle even extremely strong cultural noise successfully. The effects of the different processing techniques are demonstrated using synthetic and real data.

The data interpretation part includes several different ways of applying inversion to real field situations as well as initial attempts to integrate three-dimensional model-

ing with real data interpretation. Three-dimensional interpretation is to date still being hindered by excessive computational requirements and will be the area with the fastest growth rate.

The chapter on the field system gives the basic design criteria. The design description has been kept general enough to accommodate future technology easily, while being explicit enough to allow the reader to design his own field system using today's technology. New field procedures which can be used to improve the signal-to-noise ratio are discussed to allow a direct correlation with standard techniques.

Before going to the field it is very important that the exploration geophysicist evaluates the prospect of a successful survey. In particular, the detailed survey setup parameters and the probability of success of the technique need to be evaluated. In many instances it is important to define the necessity of additional geophysical techniques before the measurements are carried out. This can be done using the information given in the chapter on presurvey feasibility studies.

To cover the broad range of application, extensive case histories ranging from coal exploration, geothermal exploration and hydrocarbon exploration to the application of deep transient electromagnetics for deep crustal investigations are given. In particular, the chapters on joint inversion of magnetotellurics and transient electromagnetic data and the resolution of resistive layers offer new applications of the technique in hydrocarbon exploration. The first 3-D interpretation of real field data is included to illustrate that 3-D TEM is now within our reach.

Problems are included at the end of each chapter. They can be used as material for students as well as to deepen the understanding of the given information. Some of them are formulated to connect different ideas and to highlight important points.

Most of the cumbersome mathematical derivations which are of interest, but not essential, are not included in the main body but are given in the appendix. The appendix also includes a glossary, standard data formats and PC demonstration software for forward modeling.