Lecture Notes in Geosystems Mathematics and Computing

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Exploratory Potential Methods in Geothermal Power Generation

A Survey on Innovative Gravimetry and Magnetometry

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Lecture Notes in Geosystems Mathematics and Computing

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Foreword

In the year 2006, the Ministry of Economics of Rhineland-Palatinate granted start-up funding for the establishment of a research team within the Geomathematics Group of the University of Kaiserlautern, so that a research platform, the so-called "Kaiserslautern Column Model (KCM)" (cf. Figure 0.1, see also [55] for more details) could be successfully developed and applied in the field of deep geothermal energy. KCM resulted in a total of eight Ph.-D. theses in the Geomathematics Group, some of which were published in book form by renowned publishing houses.

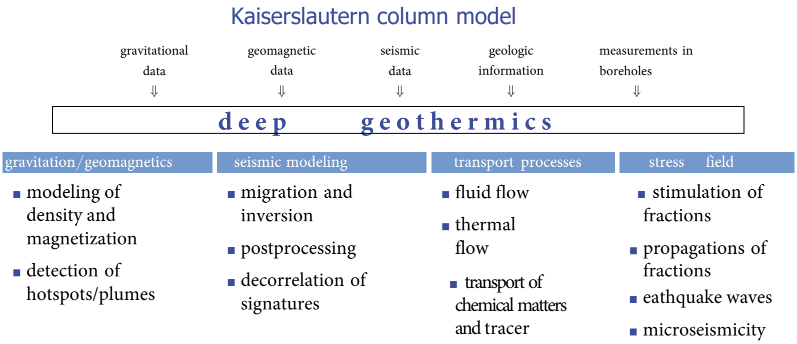

Fig. 0.1 Kaiserslautern Column Model (KCM) realized in the Geomathematics Group of the University of Kaiserslautern (2006-2016).

In the year 2012, essential parts of KCM went over to a research grant from the Federal Ministry of Economics Berlin within the framework of the joint project GEOFÜND (FKZ 0325512A-D), in which the LIAG Hannover, the Fraunhofer ITWM Kaiserslautern, the company G.E.O.S., Freiberg, and the Münchner Rückversicherung participated for a period of three years (PI Prof. Dr. W. Freeden, Geomathematics Group, University of Kaiserslautern). The main focus of the research activities was on exploratory seismic methods via new mollifier wavelet techniques, the identification of hot geothermal areas as well as the seismic specification of cost-effective drilling regions including the accompanying fractures in the deep underground.

In most European countries and, in particular, Germany, seismic is recognized as the standard method of exploration to such an extent that exploration is usually equated with seismic. However, in order to reduce the risk of drilling, it is often advisable to use gravimeter and/or magnetometer data for the analysis of geologic formations before extensive and cost-intensive seismic measurements are carried out. In order to make this observation more accessible for the exploratory practice and to provide a deepened justification, the company CBM - Gesellschaft für Consulting, Business und Management mbH, Bexbach, Saarland, decided to take up the ideas and concepts of the Geomathematics Group, University of Kaiserslautern, on decorrelative potential methods and to conduct intensive numerical test studies up to the point of usability in the exploration scenario. So, at the end of the year 2014, Prof. Dr. M. Bauer, CBM, and Prof. Dr. W. Freeden, University of Kaiserslautern, agreed to develop wavelet decorrelation of geologic structures, which had been successfully started using seismic as an example, also for the potential method of gravimetry under the auspices of the company CBM, and to validate its effectiveness in areas of the Saarland and its surroundings that are strongly influenced by anthropogenic mining. From May 2016 to April 2019, CBM realized the research project SPE (Satellite-Based Potential Methods for Geothermal Exploration, FKZ 0324061, PI Prof. Dr. W. Freeden, CBM manager Prof. Dr. M. Bauer) with the aim of developing novel concepts for the application of gravimetric potential methods for initial assessment in the planning and implementation of geothermal projects.

Based on the gravimetric research carried out in the Geomathematics Group, University of Kaiserslautern (2006-2016), the project SPE (2016-2019) provided the canonical understanding and consistent recognition that modern exploration first requires a broad range of geoscientific disciplines: In addition to geomathematics in its role as a key technology developing innovative decorrelation methods by means of multiscale analysis, geology, geophysics, and geoengineering are of essential importance. Geographers, geologists, geophysicists and geoengineers are responsible for data provision and processing as well as for the geologic evaluation and interpretation of innovative geomathematical modeling. In exploration, in fact, it is still considered a standard requirement for the successful application of potential methods based investigations that the geologic structures to be determined stand out from their surroundings by means of clear density contrasts, such as a salt dome or a magmatic hotspot. However, for example, the development of increasingly powerful absolute and relative gravimeters with significantly improved measuring accuracy and the applicability of new geomathematical mollifier methods within constructive approximation in recent years have shown that in future it will be certainly possible to detect weaker anomalies and model the "normal case of geologic layer sequences".

Since May 2019 up to April 2022, the company CBM and the TU Bergakademie Freiberg (Prof. Dr. C. Gerhards) in cooperation with the Interstate University of Applied Sciences Buchs NTB, Switzerland (Prof. Dr. M. Schreiner), had been implementing the BMWi (D) & BFO (CH) joint project "SYStematic EXPLoration" SYSEXPL (PI Prof. Dr. W. Freeden). The research project SYSEXPL was planned to run for a period of three years and was based on previous achievements of the projects GEOFÜND and SPE, in which new and efficient exploration methods for seismic and gravimetry were successfully investigated and tested. The numerical methods further developed in GEOFÜND and SPE from research results of the Geomathematics Group of the University of Kaiserslautern were transferred to magnetometry in the project SYSEXPL (PtJ FKZ 03EE4002A). The specific objective of the collaborative project SYSEXPL (PtJ FKZ 03EE4002A) was the research and development of innovative geomathematical decorrelation methods for application in magnetometry for geothermal exploration, a synoptic analysis of gravimetric decorrelation methods from the predecessor project SPE (PtJ FKZ 0324061) and the newly developed magnetometric decorrelation methods. These novel methods were prototypically applied to a test area Burbach of the Saarland using nonlinear approaches for a representation of the subsurface geology. Close cooperation took place with the project partner of the TU Bergakademie Freiberg (Prof. Dr. C. Gerhards) in the development of the analysis tool for inverse magnetometry from cleaned data. There was also a close exchange with the Swiss cooperation partner (Hochschule OST, research project REX, Prof. Dr. M. Schreiner) on the integration of the research results into the assessment tool for risk assessment of geothermal projects developed by the project REX. The final event "SYSEXPL: Systematic Exploration" at the IHK Saarland, Saarbrücken, on April 29, 2022, served to exchange information with experts and to make the project results known to the public as well as to experts.

Key literature on the development of decorrelative exploration methods that make up the survey content of the result report presented in this book are as follows: In an article published in "World of Mining" 2013, a novel method of regularizing data, the so-called mollifier methodology for decorrelation and inversion of exploration data, was proposed by W. Freeden, C. Blick [56], based on preliminary work by W. Freeden, M. Schreiner [77] in "Journal of Geodesy" (2006). Roughly speaking from a geothermal perspective, "mollification" entails the replacement of an "ill-posed" exploration problem by a system of well-posed problems that provide promising answers to ill-posedness and geologically evaluable proposed solutions. First attempts of mollifier exploration were documented numerically in the Ph.-D. thesis of the Geomathematics Group by C. Blick [28] for acoustic tomography. In the case of gravimetry, mollifier regularization using wavelets was described in detail for its mathematical/numerical ingredients by C. Blick, W. Freeden, H. Nutz [31], [32]. W. Freeden, M.Z. Nashed [64] gave a deep mathematical elaboration and methodological mollifier spline-wavelet advancements published in the "International Journal on Geomathematics" (2018). The monographs W. Freeden [54], C. Blick, W. Freeden, M.Z. Nashed, H. Nutz, M. Schreiner [34] provide an overview of the underlying theory so far and practice-relevant test and validation examples in gravimetry as well as magnetometry (additionally, C. Blick, S. Eberle [29], [30] lay the theoretical foundations for mollifier decorrelation methods in elastic seismics; the Ph.-D. thesis B. Kretz [113] deals with the transfer of essential components of mollifier methodology to poroelasticity). As a recent outcome (cf. [68]), a monograph by W. Freeden, M.Z. Nashed entitled "Recovery Methodologies–Regularization and Sampling" was published by AMS (American Mathematical Society) in August 2023, as a unifying contribution of ideas and concepts in mathematical recovery.

This work represents a numerical result report about topics to be found in the monographs W. Freeden [54], C. Blick, W. Freeden, M.Z. Nashed, H. Nutz, M. Schreiner [34], particularly in form of a georelevant collection of illustrative figures and tables. It pursues a double goal within the spectrum of geosciences: On the one side, it offers a scientific set of rules for today's geoengineering, which is interested in the application of innovative modeling and simulation techniques to promising datasets and structures. Special target groups are geoscientific institutions, engineering offices, public utilities and local energy providers as well as the entire exploration industry. On the other side, the book serves as a well understandable collection of current material in Applied Mathematics, Geophysics, and Geodesy.

In addition to the search for and acquisition of existing data, measurements of potential data of sufficiently high data density and accuracy had proven to be indispensable for purposes of decorrelative exploration. The measurement campaigns carried out by CBM, Bexbach, as the responsible institution, form an important building block for the provision of scientifically usable datasets and suitable geomathematical modeling and simulation. The programs developed in the projects SPE and SYSEXPL were designed in such a way that mainframes computers were not used as far as possible and office computers with appropriate dimensioning led to success.

Kaiserslautern, Bexbach, September 2023 *W. F., H. N.*

Preface

The book provides the geoscientific context, that arises in gravimetric/magnetometric exploration. The first step is to present a comprehensive formulation of the geoscientific framework. In addition, an insight into the current state of research is given by reducing gravimetry/magnetometry to mathematically accessible, thus, calculable and interpretable decorrelated models. In this way, the many unresolved questions and problems of gravimetry/magnetometry are to be made available to a broad geoscientific audience and the exploration industry in "mathematical appetizers". Innovative ways of utilization will be shown and new perspectives will be set in motion.

An essential characteristic of the book is its bridging function, in many ways. On the one side, the book leads in a loop from potential measurements by geoengineers particularly geodesists, through data cleansing by geophysicists, subsequent theory and model building, computer implementation and numerical calculation as well as simulation by geomathematicians, to interpretation by geologists, and back again if necessary. It thus spans the arc from geoengineering, especially geodesy, via geophysics to geomathematics and geology, and back again. On the other side, the book presents in clearly written condensed form the recently published pioneering and ground breaking multiscale mollifier methodologies realizing the transfer from the "reality space" of gravitational/magnetic measurements to the "virtual space" of mathematical/numerical mollifier wavelet decorrelations with novel geologic prospects as outcome.

The book essentially uses mathematics as a key technology for modeling and simulation issues on the basis of analysis and interpretation according to dense and precise gravitational/magnetic measurements. It is dedicated to surface and deep (volume) geology with potential data primarily of terrestrial origin. For deep geology, the geomathematical decorrelation methods are to be set up in such a way that borehole information may be canonically entered.

The work provides a consistent setup of concepts and ideas that have been already pursued by the Geomathematics Group, University of Kaiserslautern, over the last 15 years. The innovation of the work does not lie not in the basic theory of the individual chapters (in fact, some theoretical passages of the book have already been published elsewhere (see [34, 54]) in more detail according to their content). Instead, this work delivers the presentation of the underlying geomathematical philosophy and strategy in a unifying and clearly arranged synopsis, essentially on the basis of graphical illustrations and instructive numerical results.

An essential characteristic of the book is its bridging function, in many ways: The constituents of the bridging transfer from the “reality space” of observations to the ”virtuality space” of modeling solutions and vice versa form the fundamental scientific background of the whole work. So, the book presents in clearly written condensed form the recently published pioneering and ground breaking multiscale mollifier methodologies realizing the bridging transfer from gravitational/magnetic measurements and observations to mathematical/numerical mollifier wavelet decorrelations of data with novel geologic prospects as outcome. Moreover, the book leads in a loop from potential measurements by geoengineers particularly geodesists, through data cleansing by geophysicists, subsequent theory and model building, computer implementation and numerical calculation as well as simulation by geomathematicians, to interpretation by geologists, and back again if necessary. The book spans the interdisciplinary arc from geoengineering, especially geodesy, via geophysics to geomathematics and geology, and back again. In more detail, the book presents in clearly written condensed form the recently published pioneering and ground breaking multiscale mollifier methodologies realizing the bridging transfer from gravitational/magnetic measurements to mathematical/numerical mollifier wavelet decorrelations with novel geologic prospects and results as outcome.

The book can be thought of as a results and validation presentation of the ideas and concepts initiated by [56] and developed in the works [54], [34]. Using the specific example of the German Saarland region, new important fields of application, especially for areas with mining-related cavities or densely built-up area in today’s geoexploration, will be opened up and subjected to an in-depth geologic interpretation.

The success of the exploration techniques described in the book is based on the following circumstance: In explorative practice, it is still considered a standard prerequisite for the successful use of gravimetric/magnetometric investigations that the geologic structures to be determined are distinguished from their surroundings by clear density contrasts, such as a salt dome or an iron deposit. However, due to the development of increasingly powerful sensors with significantly improved measurement accuracy and the applicability of novel geomathematical methods in recent years, it appears that in the future it will also be possible to detect weaker anomalies and to model the “normal case of geologic layer sequences” by means of mollifier potential methods. Even more, synergetic effects can be obtained by comparison of gravimetric and magnetometric synopsis and the juxtoposition to seismic waves (if available).

Kaiserslautern, Bexbach, September 2023 *W. F., H. N.*

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The authors would like to thank Prof. Dr. M. Bauer for the opportunity to continue the GEOFÜND-research activities of the Geomathematics Group, University of Kaiserslautern, within the framework of the company CBM - Gesellschaft für Consulting, Business und Management mbH, Bexbach, Saarland, and to kindly take over all administrative tasks related to the research projects SPE and SYSEXPL.

The SPE measurement campaign carried out by CBM was supported in a competent manner in technical terms by the state offices of the federal states of Saarland and Rhineland-Palatinate. Special thanks go to Dipl.-Ing. T. Lehnert and Dipl.-Ing. (FH) M. Müller (State Office for Surveying, Geoinformation and Land Development Saarland, Saarbrücken) as well as Dipl.-Ing.

G. Berg and Dipl.-Ing. (FH) M. Cieslack (State Office for Surveying and Basic Geographic Information Rhineland-Palatinate, Koblenz).

The following comments can be made about the staffing and structure of the projects: Prof. Dr. W. Freeden was the scientific leader of all three projects. Dr. Nutz was in charge of the geomathematical group, Dipl.-Ing. T. Neu was in charge of the non-mathematical group. In the execution of the projects, the compilation and presentation of results in publications and reports, the management was substantially supported by the staff members Dr. C. Blick (from September 2022 professor at the University of Applied Sciences Kempten), Dr. T. Degro, M. Sc. E. Byamba, Dipl.-Geogr. B. Jakobs, Dipl.-Geol. Z. Hauler, M. Sc. B. Kretz, M. Sc. D. Krüger and Dipl.-Geophys. L. Mailänder. Without the integrative cooperation of all participants, a data acquisition by measurement, an implementation of the proposed geomathematical concepts, and the completion of the illustration and application part of this book would not have been possible.

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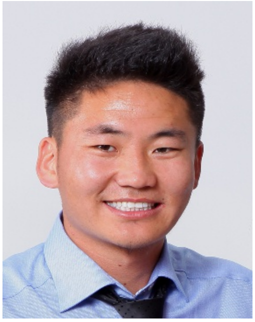

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