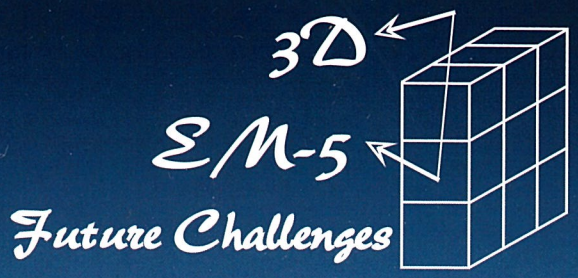
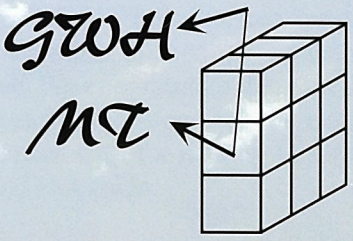


Program and Abstracts of
the 5th International Symposium on

Three-Dimensional Electromagnetics

(3DEM-5)



May 7-9, 2013

Hokkaido University Conference Hall, Sapporo, Japan

Preface

On behalf of the Gerald W. Hohmann Memorial Trust for Teaching and Research in Applied Electrical Geophysics, we would like to welcome you to the 5th International Symposium on Three-Dimensional Electromagnetics (3DEM-5), "Future Challenges".

The 3DEM symposium had been held every four years. Four highly successful symposia on 3D EM were held in Ridgefield, CT, USA (September 1995), Salt Lake City, UT, USA (October 1999), Adelaide, Australia (February 2003), and Freiberg, Germany (September 2007). 3DEM-5 was originally planned to be held in October 2011. However, the East Japan Great Earthquake that occurred on March 11, 2011 and subsequent nuclear power plant accident in Fukushima made it difficult for us to run the symposium efficiently, mainly because the Japanese geoscientists were busy with emergency field survey campaigns in the earthquake and tsunami areas. We also had anxiety over the nuclear power plant. Consequently, 3DEM-5 was postponed by more than one-and-a-half years to May 7-9, 2013. We are now very happy to be able to hold the 3DEM-5 successfully here in Sapporo, Japan, to further facilitate and accelerate the research and development of this important technology in geophysics: three-dimensional electromagnetics.

In the early 1990s, 2D EM inversion techniques were applied to field survey data as a common interpretation tool. However, we were often unsatisfied with the 2D inversion results and understood that 3D imaging is indispensable to fully understand the geological structure of our survey targets. Such demand has now been largely fulfilled, owing to recent advancements in 3D EM technology, both for data acquisition and data interpretation. A large number of 3D EM surveys have been conducted worldwide since the previous 3DEM symposium six years ago, producing many satisfactory electrical conductivity models in various fields, including natural resource exploration (petroleum, geothermal, minerals), earthquake and volcano studies, deep crustal researches, and shallow environmental and engineering problems. 3D EM surveying is now becoming one of the standard tools for oil/gas and geothermal exploration.

The role of the 3D EM technology will definitely become more important in the future. However, there exist many technological problems to be solved for obtaining more accurate, reliable and cost-effective 3D images of the subsurface. From this point, the 3D EM technology has not yet gained an established reputation in a critical community of geoscientists or geo-engineers. We still have many things to overcome. This is why the organizer of 3DEM-5 set the theme of "Future Challenges".

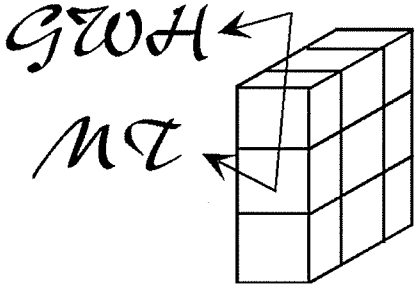
The 3DEM-5 symposium provides an optimal venue for EM scientists to discuss the future direction of 3D EM research. In particular, we hope young scientists gathering here can contribute in an active discussion and assimilate new ideas during the symposium. In the technical program, we have oral sessions in the morning, and poster sessions in the whole afternoon followed by discussion sessions. Posters are put up throughout the symposium to facilitate thorough discussion. We would like to run the program rather flexibly to encourage questions and discussions.

The organization of the 3DEM-5 has been carried out by the Local Organizing Committee, consisting of volunteer EM scientists in Japan, together with contribution of the international Technical Program Committee. We congratulate them on their wonderful job. Finally, we would like to thank the industry sponsors who supported travel expenses of students, and volunteers of Hokkaido University and Sapporo City for making this symposium run smoothly. We hope you enjoy your stay in Sapporo and Hokkaido.

May 7, 2013
Toshihiro Uchida and Toru Mogi
General Co-Chairs, 3DEM-5

GERALD W. HOHMANN MEMORIAL TRUST FOR TEACHING AND RESEARCH IN APPLIED ELECTRICAL GEOPHYSICS

The trust is an active memorial to the work of Gerald W. (Jerry) Hohmann as a scientist and educator. Jerry was an international leader in the theory and application of electrical and electromagnetic methods for the exploration of the earth's crust. His work helped establish the modern field of applied electrical geophysics. Jerry was also an outstanding teacher. As Professor of Geology and Geophysics at the University of Utah, he trained the next generation of geophysicists, who are now applying electrical and electromagnetic methods in mineral, hydrocarbon, and geothermal exploration; in groundwater, geotechnical, and environmental studies; and in regional geophysics. Jerry died from cancer on May 23, 1992 at the age of 51.



Established in November 1992, the Trust raises funds through personal donations and special events that are re-invested into education and training in electrical and electromagnetic geophysics. The Trust supports dedicated projects: the GWH undergraduate and graduate scholarships established through a matching fund program with the Society of Exploration Geophysics (SEG) Foundation, and the career achievement award established in recognition of outstanding contributions to the profession in the manner of Jerry Hohmann.

SPECIAL EVENTS:

- 1993 - Informal workshop at the University of Utah
- 1994 - a short course on electrical and electromagnetic methods at the Symposium for the Application of Geophysics for Environmental and Engineering Problems (SAGEEP)
- 2010 - State-of-the-Art in Multi-Dimensional Electromagnetics: A Special Session in Honor of Gerald W. Hohmann on Oct 20th, Weds AM of the SEG Annual Meeting, Denver CO. A toast to Jerry at the Near Surface Social, Oct 19th, Tues night at Wyncoop Brew Pub - all mining, geothermal and electrical types are cordially invited.

INTERNATIONAL SYMPOSIUM IN THREE-DIMENSIONAL ELECTROMAGNETICS (3DEM):

- 1995 - Ridgefield, Connecticut, USA
- 1999 - Salt Lake City, Utah, USA
- 2003 - Adelaide, Australia
- 2007 - Freiberg, Germany.
- **May 7-9, 2013 - Hokkaido University Conference Hall, Sapporo, Hokkaido, Japan**

GWHMT SEG UNDERGRADUATE SCHOLARSHIP:

- 1998-2000, Matthew D. Lengerich, Colorado School of Mines, USA
- 2001, David Hollema, Colorado School of Mines, USA
- 2002, Robert D. Monnar, University of Nevada, Reno, USA
- 2003-2004, Tobyn W. Van Veghten, University of Missouri, Rolla, USA
- 2005, Sasha Meyer, University of Arizona, USA
- 2006-2007, Daniel Merchant, Montana Tech, USA

- 2008, Brian Williams, Montana Tech, USA
- 2009, Jelena Makkov, University of Belgrade, Serbia
- 2010, Bray Matthew, Montana Tech, USA
- 2011, Sang Tian, University of Melbourne, Australia
- 2012, Nnaemeka Okoli, Nnamdi Azikiwe University, Nigeria

GWHMT SEG GRADUATE SCHOLARSHIP:

- 1998-2001, Kerry W. Key, SIO, University of California, San Diego, CA, USA
- 2002, Ken Yoshioka, University of Utah, UT, USA
- 2003, Thomas Gunther, Technical University, Freiberg, Germany
- 2004, Diana Dragoi, University of Houston, TX, USA
- 2005, Michael Jessop, University of Utah, UT, USA
- 2006-2007, Antje Franke, Technical University, Freiberg, Germany
- 2008, David Myer, SIO, University of California, San Diego, CA, USA
- 2009, Brent Wheelock, SIO, University of California, San Diego, CA, USA
- 2010, Murczynska Dorota, AGH Poland
- 2011-2012, Bojan Brodic, University of Belgrade, Serbia

GWH MEMORIAL AUSTRALIAN SCHOLARSHIP:

- Graduate, Aaron Davies, RMIT University, Melbourne Australia (2 yrs)
- BSc (Honours), Rachael Maier, The University of Adelaide, Adelaide Australia (1 yr)

A DECADE OF THE GWH CAREER ACHIEVEMENT AWARD

- 1997, Misac Nabighian, lifetime achievement
- 1998, David Alumbaugh, outstanding junior scientist within 5 years of completing PhD
- 1999, Douglas Oldenburg and Yaoguo Li, best paper within the last 10 year
- 2000, Stanley Ward, in support of the SEG Ewing Award
- 2001, Ulrich Schmucker, outstanding educator
- 2002, Kurt Sorensen and Max Meju, direct benefit to society
- 2003, Steven Constable and Gerald Minerbo, O&G exploration
- 2004, Yves Lamontagne, practical achievement in mineral exploration
- 2005, Nigel Edwards, numerical modeling
- 2006, Adele Manzella and Toshihiro Uchida, geothermal resources
- 2007, Art Raiche, lifetime achievement

TRUSTEES - ACTIVE

- George Jiracek
- Michael Oristaglio
- Louise Pellerin
- Klaus Spitzer
- Philip Wannamaker

TRUSTEES - HONORARY

- Aileen Hohmann, family representative

5th International Symposium on Three-Dimensional Electromagnetics
"Future Challenges"

May 7-9, 2013
Conference Hall, Hokkaido University, Sapporo, Japan

Co-Organizers:
Gerald W. Hohmann Memorial Trust for Teaching and Research in Applied Electrical Geophysics
Institute for Geo-Resources and Environment, AIST
Institute of Seismology and Volcanology, Hokkaido University

Supporters:
Society of Exploration Geophysicists of Japan (SEGJ)
Society of Exploration Geophysicists (SEG)

General Co-Chairs:
Toshihiro Uchida, Geological Survey of Japan, AIST
Toru Mogi, Hokkaido University

Technical Program Committee:
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David Alumbaugh, Chevron, USA (Co-Chair)
Grant Caldwell, GNS Science, New Zealand
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George Jiracek, San Diego State University, USA
Kerry Key, Scripps Institution of Oceanography, USA
Hee Joon Kim, Pukyong National University, Korea
Alexey Kuvshinov, ETH Zurich, Switzerland
Louise Pellerin, Green Geophysics, USA
Klaus Spitzer, TU Bergakademie Freiberg, Germany
Phil Wannamaker, University of Utah, USA

Local Organizing Committee:
Toshihiro Uchida, Geological Survey of Japan, AIST (Chair)
Toru Mogi, Hokkaido University (Co-Chair)
Yasuo Ogawa, Tokyo Institute of Technology (Co-Chair)
Tadanori Goto, Kyoto University
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Toshio Kasagi, Nittetsu Mining Consultants Co., Ltd.
Tae Jong Lee, Korea Institute of Geoscience & Mineral Resources (KIGAM)
Keiko Nakayama, Waseda University
Yutaka Sasaki, Kyushu University
Tatsuya Sato, Geothermal Energy Research and Development Co., Ltd. (GERD)
Koichi Suzuki, Central Research Institute of Electric Power Industry (CRIEPI)
Takumi Ueda, Geological Survey of Japan, AIST
Makoto Uyeshima, University of Tokyo
Kazunobu Yamane, Japan Oil, Gas and Metals National Corporation (JOGMEC)
Ryokei Yoshimura, Kyoto University

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GERD Geothermal Energy Research & Development Co., Ltd.	INPEX INPEX Corp.
MINDECO 三井金属資源開発株式会社 Mitsui Mineral Development Engineering Co., Ltd.	NMCC Nittetsu Mining Consultants Co., Ltd. Nittetsu Mining Consultants Co., Ltd.
OYO oyo corporation OYO Corp.	SRED Sumiko Resources Exploration & Development Co., Ltd.

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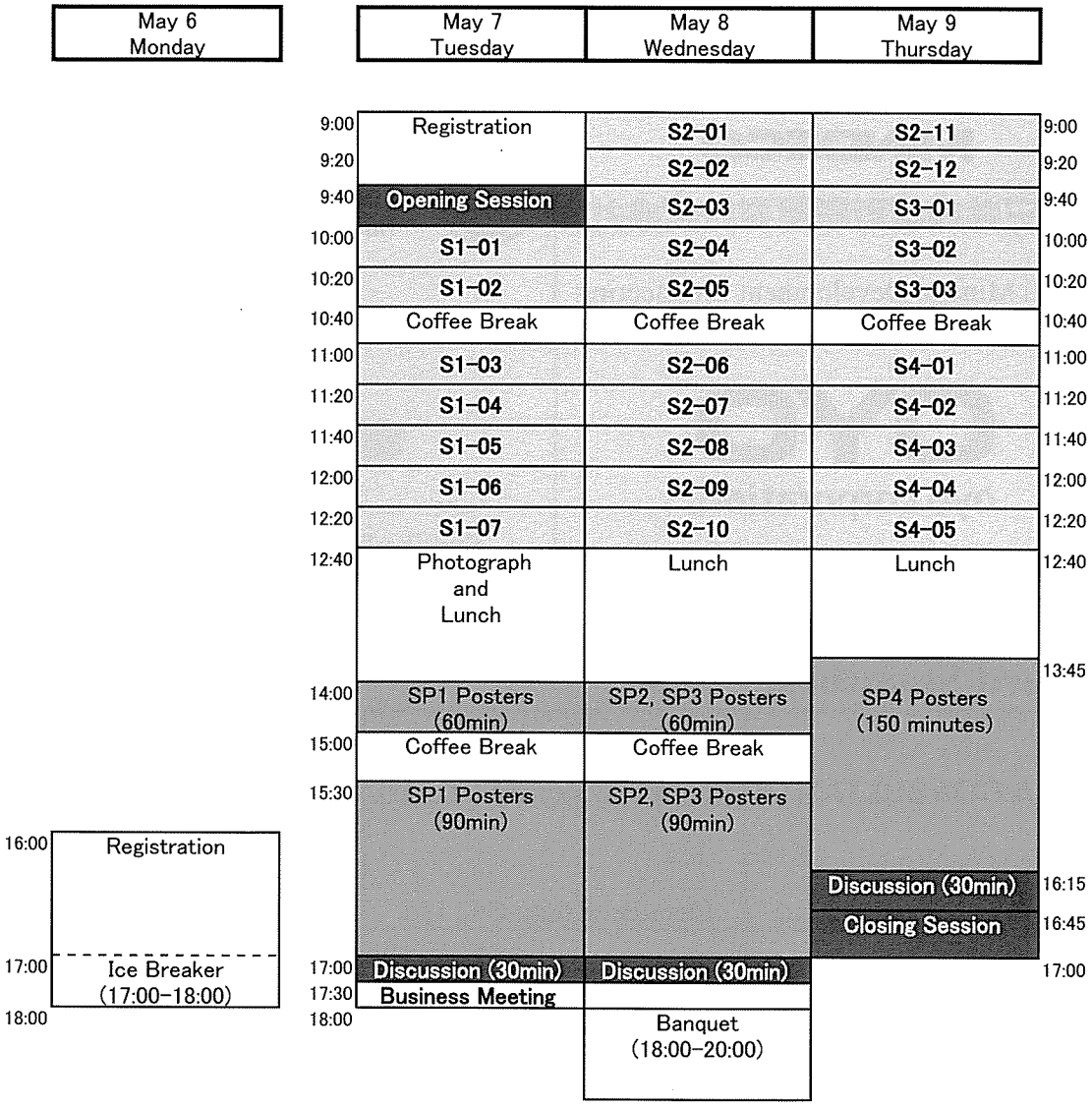
Exhibitor:

GEOMETRICS Innovation • Experience • Results

Geometrics Inc.

Overall Schedule



Session	
S1, SP1:	Forward Modeling
S2, SP2:	Inversion and Resolution Analysis
S3, SP3:	New Methodologies
S4, SP4:	Applications

3DEM-5 Technical Program

May 7 (Tuesday)

9:40 ~ 10:00 **Opening Session**

10:00 ~ 12:40 **Session 1 Forward modeling**
Chairs: Klaus Spitzer, Tada-nori Goto

S1-01 (10:00~) *J. Koldan, V. Puzyrev and J. M. Cela*
Parallel Finite-Element Method for 3-D Electromagnetic Modelling in Geophysics

S1-02 (10:20~) *Z. Ren, T. Kalscheuer, S. Greenhalgh and H. Maurer*
A goal-oriented adaptive finite-element approach for plane wave 3D electromagnetic modeling

(Coffee Break)

S1-03 (11:00~) *M. Kordy, V. Maris, P. Wannamaker and E. Cherkaev*
3D Edge Finite Element Solution for Scattered Electric Field using a Direct Solver Parallelized on an SMP Workstation

S1-04 (11:20~) *H. Jahandari and C. G. Farquharson*
Finite volume modelling of electromagnetic data using unstructured staggered grids

S1-05 (11:40~) *M. Cherevatova, G. D. Egbert, M. Y. Smirnov and A. Kelbert*
3D electromagnetic modeling using multi-resolution approach

S1-06 (12:00~) *B. Zhou, G. Heinson and A. Rivera-Rios*
Frequency-domain 3D geo-electromagnetic modeling with sub-domain Chebyshev spectral method

S1-07 (12:20~) *J. Sun and A. Kuvshinov*
Accelerating an EM integral equation forward solver for global geomagnetic induction using SVD based matrix decomposition method

(Photograph and Lunch Break)

14:00 ~ 17:00 **Poster (Session 1)**
17:00 ~ 17:30 **Discussion (Session 1)**
17:30 ~ 18:00 **Business meeting**

May 8 (Wednesday)

9:00 ~ 12:40 **Session 2 Inversion and Resolution Analysis**

Chairs: Hee Joon Kim, Alexey Kuvshinov

S2-01 (9:00~) *G. Egbert, A. Kelbert and N. Meqbel*
ModEM: developing 3D EM inversion for the masses

S2-02 (9:20~) *M. S. Zhdanov, M. Endo, L. H. Cox and M. Čuma*
Recent advances in three-dimensional large-scale electromagnetic modeling and inversion

S2-03 (9:40~) *D. Yang, D. Oldenburg and E. Haber*
Massive parallelization of 3D electromagnetic inversion using local meshes

S2-04 (10:00~) *J. Bakker and A. Kuvshinov*
A novel 3-D MT inverse solver: its implementation and outlook

S2-05 (10:20~) *W. Wilhelms, R.-U. Börner and K. Spitzer*
Preparation for a 3D magnetotelluric inversion -- specific characteristics of the all-at-once approach

(Coffee Break)

Chairs: Sophie Hautot, Ryokei Yoshimura

S2-06 (11:00~) *Y. Sasaki*
Anisotropic 3D inversion of marine CSEM data

S2-07 (11:20~) *A. Kuvshinov and O. Pankratov*
Towards quantitative resolution analysis of 3-D EM inversion results. Efficient calculation of the Hessian matrix of frequency-domain EM data misfit using adjoint sources approach

S2-08 (11:40~) *N. Imamura, T. Goto, J. Takekawa and H. Mikada*
Resolution of full waveform inversion using controlled-source electromagnetic exploration

S2-09 (12:00~) *M. S. G. McMillan and D. W. Oldenburg*
Enhancing Resolution of 3D-EM Inversion Models through a Co-operative Approach

S2-10 (12:20~) *N. Meqbel and O. Ritter*
New Advances for a joint 3D inversion of multiple EM methods

(Lunch Break)

14:00 ~ 17:00 **Poster Session (Session 2, 3)**
17:00 ~ 17:30 **Discussion (Session 2)**
18:00 ~ 20:00 **Banquet**

May 9 (Thursday)

9:00 ~ 9:40 **Session 2 Inversion and Resolution Analysis**
Chairs: Alexey Kuvshinov, Ryokei Yoshimura

S2-11 (9:00~) *M. A. Meju*
Tailored fit-for-purpose 3D interpretation of marine CSEM data

S2-12 (9:20~) *G. A. Newman, E. Um and M. Commer*
A Framework for three-dimensional coupled seismic-electromagnetic inversion

9:40 ~ 10:40 **Session 3 New Methodologies**
Chairs: Louise Pellerin, Grant Caldwell

S3-01 (9:40~) *A. Geraskin*
Programming in 3-D electromagnetics: look from outside

S3-02 (10:00~) *J. Börner, M. Afanasjew, F. Eckhofer, J. Weißflog and K. Spitzer*
Monitoring concepts using borehole transient electromagnetic and DC resistivity methods: 3D simulation studies for the effective detection of CO2 leakages

S3-03 (10:20~) *R. Peng, X. Hu, Y. Liu and Z. He*
The potential of magnetotelluric using for reservoir monitoring

(Coffee Break)

11:00 ~ 12:40 **Session 4 Applications**
Chairs: Phil Wannamaker, George Jiracek, Hiroshi Ichihara

S4-01 (11:00~) *K. Noh, Y. Chung, S. J. Seol, J. Byun and T. Uchida*
Three-dimensional inversion of small-loop electromagnetic data: Water leak detection in an artificial sandy ground

S4-02 (11:20~) *A. Rödder and B. Tezkan*
Transient electromagnetic survey on the Araba fault, Jordan: A 3D conductivity model

S4-03 (11:40~) *S. Hautot and P. Tarits*
Importance of the MT diagonal tensor coefficients for 3D inversion

S4-04 (12:00~) *E. Bertrand, T. G. Caldwell, G. J. Hill and S. L. Bennie*
3-D inversion of a 200+ site magnetotelluric array for deep geothermal exploration

S4-05 (12:20~) *N. Tada, K. Baba and H. Utada*
Three-dimensional electrical conductivity structure beneath the Philippine Sea using three-dimensional marine MT inversion dealing with topographic effect

(Lunch Break)

13:45 ~ 16:15 **Poster Session (Session 4)**
16:15 ~ 16:45 **Discussion (Session 3, 4)**
16:45 ~ 17:00 **Closing Session**

Posters

Session 1 Forward modeling (14:00~17:00, May 7)

SP1-01 *A. M. Rivera-Rios, B. Zhou, G. Heinson and S. Thiel*
Multi-order Vector Finite Element Modelling of 3D Magnetotelluric Data including complex geometry and anisotropic earth

SP1-02 *A. Franke-Börner, R.-U. Börner and K. Spitzer*
Convergence studies for the finite element simulation of the 3D MT boundary value problem

SP1-03 *M. G. Persova, Y. G. Soloveichik, M. G. Tokareva, P. A. Domnikov, D. V. Vagin and T. G. Shashkova*
Finite element 3D Modeling of Geoelectromagnetic Fields for Controlled and Natural Sources

SP1-04 *M. Afanasjew, R.-U. Börner, M. Eiermann, O. G. Ernst and K. Spitzer*
Efficient Three-Dimensional Time Domain TEM Simulation Using Finite Elements, a Nonlocal Boundary Condition, Multigrid, and Rational Krylov Subspace Methods

SP1-05 *R.-U. Börner, O. G. Ernst and S. Güttel*
Three-dimensional transient electromagnetic simulation using Rational Krylov subspace projection methods

SP1-06 *S. Ansari and C. G. Farquharson*
Three dimensional modeling of controlled-source electromagnetic response for inductive and galvanic components

SP1-07 *T. Koyama*
Forward modeling for CSEM excited by the cable current with finite length

SP1-08 *S. A. Allah, T. Mogi and E. Fomenko*
Three-dimensional electromagnetic modeling of sea and topographic effects on electromagnetic field induction by grounded electrical source airborne transient electromagnetics (GREATEM) survey systems

SP1-09 *X. Zhou, X. Hu and B. Han*
3D finite-difference time-domain forward modeling with convolutional perfectly matched layers (CPML) absorbing boundary condition for marine CSEM

SP1-10 *D. V. Shantsev and F. A. Maaø*
Rigorous interpolation near interfaces in 3D finite-difference EM modeling

SP1-11 *M. Sommer, S. Hölz, M. Moorkamp, A. Swidinsky, B. Heincke, C. Scholl and M. Jegen*
Speeding up a marine 3D CSEM code with GPU

SP1-12 *J. Ge, M. E. Everett and C. J. Weiss*
3D modeling of fractional diffusion to describe electromagnetic induction in fractured geological media

Session 2 Inversion and Resolution Analysis (14:00~17:00, May 8)

SP2-01 *C. Püthe and A. Kuvshinov*
Mapping 3-D mantle electrical conductivity from space. Development of a new 3-D inversion scheme based on analysis of matrix Q-responses

SP2-02 *S. Schnaidt and G. Heinson*
Bootstrapping as a means of uncertainty analysis in inversion modelling of magnetotelluric data

SP2-03 *K. Tietze, O. Ritter and G. Egbert*
3D inversion of magnetotelluric phase tensor and apparent resistivity & phase data with ModEM and its application to a 250-site MT array data set from the San Andreas fault, California

SP2-04 *T. J. Lee, J. Choi, J. Yang, S. K. Lee, I.-H. Park and Y. Song*
An approach for the three-dimensional interpretation of MT data distorted by the sea- and static effects

SP2-05 *M. Tani, H. Mikada, T. Goto, J. Takekawa and W. Siripunvaraporn*
Removable of galvanic distortion on 3-D MT inversion

SP2-06 *O. Peredo, V. Puzyrev, J. Koldan, G. Houzeaux, M. Vázquez, J. de la Puente and J. M. Cela*
Inverse modelling of 3D Controlled-Source Electromagnetics using a Parallel Discrete Adjoint method

SP2-07 *C. Schwarzbach and E. Haber*
Inversion of large scale airborne time domain electromagnetic data

SP2-08 *M. Scheunert, M. Afanasjew, R.-U. Börner, M. Eiermann, O. G. Ernst and K. Spitzer*
3-D inversion of helicopter electromagnetic data

SP2-09 *F. Eckhofer, J. Weißflog, R.-U. Börner, M. Eiermann, O. G. Ernst and K. Spitzer*
Regularization for 3D DC resistivity inversion

SP2-10 A. *D. Garnadi and H. Grandis*
Gauss-Newton inversion algorithm to estimate resistivity parameter using a dual-optimal grid approach

SP2-11 *M. G. Persova, Y. G. Soloveichik, M. G. Tokareva, P. A. Domnikov, M. V. Abramov, D. V. Vagin and E. I. Simon*
Three-dimensional inversion for transient electromagnetic sounding technologies with loop source and for induced polarization using finite element approximation

Session 3 New Technologies (14:00~17:00, May 8)

SP3-01 *A. Ullmann, B. Siemon and M. Miensopust*
Automatic detection and classification of induction anomalies in helicopter-borne electromagnetic data sets

SP3-02 *S. K. Verma, T. Mogi, S. A. Allah, S. P. Sharma and E. Fomenko*
3D 'Tau' imaging of subsurface conductors by contemporary helicopter borne time domain EM systems

SP3-03 *R. Streich, M. Becken and O. Ritter*
Robust processing of onshore controlled-source electromagnetic data from a three-phase galvanic source

SP3-04 *D. Hyodo, H. Mikada, T. Goto and J. Takekawa*
Downward-continued pseudo resistivity section using normalized full gradient (NFG) in VLF-EM method

Session 4 Applications (13:45~16:15, May 9)

SP4-01 *N. Zorin and A. Yakovlev*
Telluric method of natural field induced polarization

SP4-02 *L. Zhang, H. Utada, H. Shimizu, K. Baba and T. Maeda*
Three-dimensional simulation of the electromagnetic fields induced by tsunamis: A case study for the 2011 Tohoku Tsunami

SP4-03 *K. Okazaki, Y. Ito, T. Mogi, H. Ito, Y. Yuuki and A. Jomori*
Case study of three-dimensional geotechnical evaluations for tunnel design and construction by helicopter-borne geophysical survey

SP4-04 *M. P. Miensopust, B. Siemon and A. Ullmann*
Three-dimensional modeling of frequency-domain helicopter-borne electromagnetic data: A case study of the Cuxhaven Valley

SP4-05 *A. Grayver, R. Streich and O. Ritter*
3D inversion of land-based CSEM data from the Ketzin CO2 storage formation

SP4-06 *A. Younis, G. EL-Qady, M. A. Abdalla, M. Abdel Zaher, A. E. khalil and M. G. Al Ibiary*
Integrated geophysical tools for hydrocarbon exploration in Nile delta area, Egypt

SP4-07 *A. Avdeeva, M. Y. Smirnov, A. S. Savvaidis, M. Gurk and L. B. Pedersen*
A 3D magnetotelluric study of the basement structure in the Mygdonian Basin (Northern Greece) including galvanic distortion correction.

SP4-08 *H. Ichihara, T. Mogi, K. Tanimoto, Y. Yamaya, T. Hashimoto, M. Uyeshima and Y. Ogawa*
3-D electrical resistivity models in the Erimo area, southern central Hokkaido

SP4-09 *T. Uchida and T. Ueda*
Three-dimensional magnetotelluric survey over Yunodake and Idosawa Faults in Iwaki area, Fukushima Prefecture

SP4-10 *Y. Yamaya, T. Mogi, R. Honda, H. Hase, A. Suzuki, T. Hashimoto and M. Uyeshima*
Three-dimensional Resistivity Imaging beneath the Fold-and-thrust Belt, Ishikari-teichi-toen Fault Zone, Hokkaido, NE Japan

SP4-11 *T. G. Caldwell, W. Heise, Y. Ogawa, G. J. Hill, E. A. Bertrand, S. L. Bennie, H. M. Bibby and G. R. Jiracek*
Electrical conductivity structure of the Alpine Fault, New Zealand - a 3D anisotropic problem

SP4-12 *T. Kaya, Y. Ogawa, T. Kasaya, S. B. Tank, M. K. Tunçer, N. Oshiman, Y. Honkura, M. Matsushima, and W. Siripunvaraporn*
Investigation of the lithospheric structures and North Anatolian Fault Zone underneath the Marmara Sea by 3D Magnetotelluric modeling.

SP4-13 *F. Febriani, P. Han, C. Yoshino, K. Hattori, B. Nurdiyanto, N. Effendi, I. Maulana, Suhardjono, P. Hardjono and E. Gaffar*
2D inversion of Pelabuhan Ratu magnetotelluric data, Indonesia

SP4-14 *R. Yoshimura, Y. Ogawa, Y. Yukutake, W. Kanda, S. Komori, T. Goto, R. Honda, M. Harada, T. Yamazaki, M. Kamo, Y. Yasuda and M. Tani*
Heterogeneous resistivity structure around high seismicity regions in Hakone volcano, Japan

SP4-15 *Y. Ogawa, H. Fukino, M. Ichiki, and W. Kanda*
Three-dimensional imaging of fluids under the volcanic arc, around Naruko Volcano, NE Japan

SP4-16 *M. Hata, N. Oshiman, R. Yoshimura, Y. Tanaka and M. Uyeshima*
Interpretation on magmatism beneath the Kyushu subduction zone with 3D electrical resistivity image

SP4-17 *M. Uyeshima, S. Yamaguchi, H. Murakami, T. Tanbo, R. Yoshimura, H. Ichihara and K. Omura*
On elucidation of the regional anomalous phase contained in the Network-MT data in the Chubu district, central Japan

SP4-18 *N. Meqbel, G. D. Egbert and P. E. Wannamaker*
Three dimensional modelling of a large scale magnetotelluric data: Final results from 3-D inversion of the US-Transportable Array

SP4-19 *K. Baba, N. Abe, N. Hirano and M. Ichiki*
Three-dimensional inversion analysis of seafloor magnetotelluric data collected in the northwestern Pacific and implications for the source of petit-spot volcanoes

S1-01

Parallel Finite-Element Method for 3-D Electromagnetic Modelling in Geophysics

Jelena Koldan[1], Vladimir Puzyrev[1] and José María Cela[1]
[1]Barcelona Supercomputing Center, Computer Applications in Science & Engineering (CASE) Department

SUMMARY

We have developed a parallel nodal finite-element solver for three-dimensional electromagnetic numerical modelling in geophysics. The method can be used for modelling different controlled-source and magnetotelluric problems in anisotropic media. Due to the fact that it supports completely unstructured tetrahedral meshes as well as mesh refinement, it is possible to represent complex geological structures very precisely and thus improve the solution accuracy. In addition, the parallel implementation of the method has proved to be highly scalable – the achieved speed-up is close to linear for up to thousands of processors. Thanks to this, the code is able to deal with extremely large problems, which may have tens of millions of degrees of freedom, in a very efficient way. Considering that efficiency of the forward-problem solver is critical for its future use inside of a 3-D inversion algorithm, we have developed different preconditioning schemes for Krylov subspace methods, namely approximate inverse based and algebraic multigrid based preconditioners. Tests for various problems with different conductivity structures and characteristics have shown that, our preconditioners greatly improve the convergence of different iterative solvers and significantly reduce the total execution time of the program.

Keywords: forward modelling, finite element, preconditioning, algebraic multigrid

S1-02

A goal-oriented adaptive finite-element approach for plane wave 3D electromagnetic modeling

Zhengyong Ren, Thomas Kalscheuer, Stewart Greenhalgh and Hansruedi Maurer
Institute of Geophysics, Department of Earth Sciences, ETH Zurich

SUMMARY

We have developed a novel goal-oriented adaptive mesh refinement approach for finite-element methods to model plane wave electromagnetic fields in 3D earth models based on the electric field differential equation. To handle complicated models of arbitrary conductivity, magnetic permeability and di-electric permittivity involving curved boundaries and surface topography, we employ an unstructured grid approach. The electric field is approximated by linear curl-conforming shape functions which guarantee the divergence-free condition of the electric field within each tetrahedron and continuity of the tangential component of the electric field across the interior boundaries. Based on the non-zero residuals of the approximated electric field and the yet to be satisfied boundary conditions of continuity of both the normal component of the total current density and the tangential component of the magnetic field strength across the interior interfaces, three a-posterior error estimators are proposed as a means to drive the goal-oriented adaptive refinement procedure. The first a-posterior error estimator relies on a combination of the residual of the electric field, the discontinuity of the normal component of the total current density and the discontinuity of the tangential component of the magnetic field strength across the interior faces shared by tetrahedra. The second a-posterior error estimator is expressed in terms of the discontinuity of the normal component of the total current density (conduction plus displacement current). The discontinuity of the tangential component of the magnetic field forms the third a-posterior error estimator. Based on numerical examples, we found that the error estimator using face jumps of normal components of current density embedded in the goal-oriented adaptive refinement procedure shows the most efficient performance.

Keywords: finite element, goal-oriented adaptive refinement, magnetotelluric, plane wave

S1-03

3D Edge Finite Element Solution for Scattered Electric Field using a Direct Solver Parallelized on an SMP Workstation

Michal Kordy[1,2], Virginie Maris[1], Phil Wannamaker [1] and Elena Cherkaev[2]
[1]Energy and Geoscience Institute at the University of Utah
[2]Department of Mathematics at the University of Utah

SUMMARY

We have implemented an edge finite element solution to simulate the Helmholtz equation for scattering of the electric field from subsurface electrical conductivity structure. First-order elements on hexahedral grid are used where the electric field is constant along the edges and varies linearly between edges. Choosing this basis allows the incorporation of topography through deformation of the mesh, and yields a relatively compact system matrix structure. The frequency range considered is appropriate for diffusive EM propagation in a conducting earth, but we retain dielectric properties for the air medium. A secondary E-field formulation is used that facilitates arbitrary impressed sources, which we have tested so far using plane-wave (MT) source fields. Several factors discussed herein have motivated us to migrate from iterative to direct system matrix solvers. Using a matrix tiling approach too parallelizing the modified Cholesky (LDLT) factorization, we have achieved excellent scalability on a 24-core workstation with 0.5 TB RAM. However, use of a direct solution even with double precision arithmetic does not necessarily escape parasitic E-fields in the form of gradient of a scalar potential, especially in the air. Hence, a divergence correction also using a parallelized direct solver was implemented and successfully recovers the correct field. The magnetic field, obtained by curl of E, is not affected by this problem. Good agreement using this solution is obtained for conductive and resistive prisms in a half space, and for a simple hill structure, in comparison to other approaches.

Keywords: forward modeling, finite element, divergence correction, multicore CPU, direct solver, edge elements

S1-04

Finite volume modelling of electromagnetic data using unstructured staggered grids

Hormoz Jahandari[1], and Colin G. Farquharson[1]
[1]Memorial University of Newfoundland, St. John's, NL, Canada

SUMMARY

Unstructured schemes possess important advantages in the modelling of total electromagnetic fields where the source location is required to be highly refined, and in the simulation of topographic features of the terrain and geological interfaces. This study investigates the application of the well-known Yee's staggered scheme to unstructured Delaunay-Voronoï grids. The Helmholtz equation for the electric field is discretized using a finite volume approach and the problem is solved for the projection of the total electric field along the Delaunay edges. Edge vector basis functions are used for interpolation inside the tetrahedra and for recovering magnetic fields. As examples for this preliminary study, the responses of a homogeneous half-space and a conductive block in a resistive background to magnetic dipole sources are computed and compared with analytical results.

Keywords: electromagnetics, forward modeling, finite difference, finite volume, unstructured grids

S1-05

3D electromagnetic modeling using multi-resolution approach

Maria Cherevatova[1], Gary D. Egbert[2], Maxim Yu. Smirnov[1] and Anna Kelbert[2]
[1]University of Oulu, Finland
[2]Oregon State University, Oregon, USA

SUMMARY

We present a multi-resolution approach for 3D forward electromagnetic (EM) modeling and inversion. Development of the technique is motivated by the fact that a finer grid resolution is often required in the near surface to adequately represent near surface inhomogeneities and topography. On the other hand, the EM fields propagate in a diffusive manner and can be sufficiently well described on a grid that becomes gradually coarser with depth. A multi-resolution approach, therefore, provides a means to significantly decrease the number of degrees of freedom and hence improve on computational efficiency without significantly compromising the accuracy of the solution.

In our implementation, the full grid is represented as a vertical stack of sub-grids, each of which is a standard staggered grid. The grid is refined only in the horizontal direction, uniformly across vertical layers, allowing only factor of two between vertically adjacent sub-grids, and is thus a simplified quadtree scheme. In the present work we describe the grid design and setting of the corresponding operators.

A major difficulty lies in discretizing the forward operator around the interfaces. To maintain efficiency of iterative solvers, and to simplify adjoint sensitivity calculations for inversion applications it is desirable to preserve symmetry of discretized operators. In particular, the discretized operator $\nabla \times \nabla \times$ needs to be self-adjoint, and the operators $\nabla \cdot$ and ∇ should be adjoints of each other (with respect to appropriate inner products). We describe a first order accurate approach to compute these operators that preserves these symmetries. We have run synthetic tests to compare 3D solver accuracy relative to 2D solution. The responses through the center of the infinite prism and corresponding 2D cube model yields phase difference of 0.2 °. The improvement in speed of forward solver reaches 3 – 6 times and memory requirements 1.5 – 3 for the larger models.

Keywords: multi-resolution, forward modeling, inversion, finite difference

S1-06

Frequency-domain 3D geo-electromagnetic modeling with sub-domain Chebyshev spectral method

Bing Zhou, Graham Heinson and Aixa Rivera-Rios
Department of Geology and geophysics, The University of Adelaide

SUMMARY

We propose a new numerical modeling method for 3D geo-electromagnetic fields which are measured in magnetotelluric or controlled-source electromagnetic survey. The new scheme utilizes a curved coordinate system to match the free-surface topography and subsurface interfaces, and applies the Chebyshev spectral method to differentiations of the generalized governing equations. We adapt the normal global differentiation scheme to a sub-domain scheme so that the assembled matrix becomes sparse but remains having high accuracies for the numerical differentiations. Our numerical tests show that the sub-domain Chebyshev differentiations are superior to the traditional finite-difference methods in the accuracy of differentiations. Meanwhile, we investigated the effectiveness of the generalized perfectly matched layer applied to the 3D modeling. The initial results show success in removing the influences of artificial boundaries truncating the infinite computational domain into a reasonable size, and encourage us to explore more benefits of the proposed technique.

Keywords: geo-electromagnetic fields, 3D modeling, perfectly matched layer, Chebyshev spectral method.

S1-07

Accelerating an EM integral equation forward solver for global geomagnetic induction using SVD based matrix decomposition method

Jin Sun[1], and Alexey Kuvshinov[1]
[1] Institute of Geophysics, ETH Zurich, Switzerland

SUMMARY

We develop an SVD based recursive decomposition of the system matrix of an EM integral equation forward solver for global geomagnetic induction, on top of an FFT reduction of the system to a block-diagonal form. With this approach, the memory cost and computational complexity of Krylov subspace iterative solutions are significantly reduced, making the accelerated forward solver suitable for 3-D inversions. We explore different implementation schemes to assess the effectiveness of this method.

Keywords: 3-D forward modeling, integral equation, matrix decomposition, fast algorithm

S2-01

ModEM: developing 3D EM inversion for the masses

Gary Egbert[1], Anna Kelbert[1] and Naser Meqbel[2]
[1]College of Earth, Oceanic, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA
[2]GFZ German Research Centre for Geosciences, Potsdam, Germany

SUMMARY

ModEM is a prototype modular system for inversion of EM geophysical data, which has been developed over the past years at Oregon State University, and applied to 2D and 3D magnetotellurics (MT), global induction studies, and in test applications, to controlled source EM problems. For several years ModEM has been made available to collaborators at other institutions, in some cases leading to extension and refinements to the code. More recently we have provided the 3D MT inversion code on an "as is, users beware" basis, and are now in the early stages of an NSF funded project to extend, "harden", maintain and more fully support broad use of ModEM. Our primary initial focus is on support of the 3D MT capabilities, although we also are working to build on the more general capabilities of ModEM to support inversion of CSEM data, and joint inversion of multiple EM (and ultimately other) data types. In addition to development and maintenance of software, we will offer training in 3D MT inversion, and maintain a web presence where the community of ModEM users can discuss with us and each other problems and solutions as they arise, and develop and provide short courses on 3D MT inversion and interpretation.

Keywords: inversion, electromagnetic geophysics, magnetotellurics, software, CSEM

S2-02

Recent advances in three-dimensional large-scale electromagnetic modeling and inversion

Michael S. Zhdanov[1,2], Masashi Endo[1], Leif H. Cox[1], and Martin Čuma[1,2]
[1]TechnoImaging, Salt Lake City UT
[2] Consortium for Electromagnetic Modeling and Inversion, University of Utah, Salt Lake City UT

SUMMARY

This paper reviews recent advances in 3D EM modelling and inversion, based on integral equation (IE) method. While the basic theory of the IE method has long been established, advances in algorithms, software engineering, and computing resources have significantly expanded the IE method's capabilities and applications. We demonstrate in this paper how the IE method can simulate the same model complexity as finite-difference (FD) or finite-element (FE) methods, while providing efficient inversion algorithms. We present the case studies for the inversion of the marine and airborne EM data for very large-scale 3D earth models.

Keywords: 3D, electromagnetic, modeling, inversion, integral equations, large-scale.

S2-03

Massive parallelization of 3D electromagnetic inversion using local meshes

Dikun Yang[1], Douglas Oldenburg[1], Eldad Haber[1]
[1]Geophysical Inversion Facility, University of British Columbia

SUMMARY

Despite recent advances of algorithms and computing techniques, speed remains one of the major concerns for practical 3D EM modeling and inversion. To reduce run times, we develop a generic parallelization scheme for modeling EM fields in the diffusive regime using local meshes that have fine-scale discretization near the locations of transmitter and receiver. If the sizes of transmitter and receiver are relatively small, a local mesh that exclusively serves one transmitter-receiver pair can be much smaller and easier to solve than a universal (global) mesh that is good for every transmitter and receiver. Local meshes thus allow a large EM problem to be decomposed to many small highly independent problems, and massive parallelization can be effectively applied. Two control-source EM surveys are considered in this paper: an airborne EM survey and a large ground loop EM survey, for which different types of local mesh are designed according to the configurations of the systems. We show that the local mesh method is capable of providing adequate accuracy in forward modeling and in the sensitivity computation. A synthetic example of inversion shows nearly linear speedup as the number of processors increases. We illustrate the technique with an airborne EM field data example.

Keywords: electromagnetic, forward modeling, inversion, parallelization, local mesh

S2-04

A novel 3-D MT inverse solver: its implementation and outlook

Jenneke Bakker and Alexey Kuvshinov
Institute of Geophysics, ETH Zurich, Switzerland

SUMMARY

We are developing a modular three-dimensional (3-D) magnetotelluric (MT) inverse solver. As a forward modeling engine an integral equation (IE) approach is used and the inversion itself is based on an iterative gradient-type optimization method. The adjoint approach is invoked to calculate the gradient of the misfit. Besides the impedance tensor, also the horizontal magnetic tensor, tippers and the phase tensor can be employed. Here, we present the implementation and an outlook for extensions of our inverse solver.

Keywords: magnetotellurics, 3-D inversion, adjoint approach

S2-05

Preparation for a 3D magnetotelluric inversion – specific characteristics of the all-at-once approach

Wenke Wilhelms, Ralph-Uwe Börner, and Klaus Spitzer
TU Bergakademie Freiberg

SUMMARY

The all-at-once inversion approach requires no explicit forward calculation, because the forward modelling equations are incorporated in the objective function as constraints. This leads to a huge, so-called Karush-Kuhn-Tucker (KKT) system, which is solved in each step of the iteration procedure to update model parameters, Lagrangian multipliers, and data - all at once. Still, the forward problem needs detailed consideration, because the system matrix of the forward problem is necessary to calculate first and second derivatives for setting up the KKT matrix. Our all-at-once inversion results for the 1D magnetotelluric problem are promising. As necessary prerequisite for a 3D inversion we successfully implemented and validated a 3D forward operator. Forming the Hessian, i.e., the matrix containing second derivatives required in a Newton step, is key in the all-at-once approach. Besides regularization, we emphasize the chosen method of calculating the residual. Since the 3D magnetotelluric forward response is represented by two linear independent solutions of equation systems, the data has to be formed as a linear combination of electric field values and their spatial derivatives, the magnetic fields. We reformulate the problem by scaling the measured impedances with the magnetic fields obtained from the forward step, thus eliminating the non-trivial step of forming impedances from numerical results alone. The resulting KKT system can be solved using Krylov subspace projection techniques.

Keywords: magnetotellurics, 3D inversion, finite differences, all-at-once

S2-06

Anisotropic 3D inversion of marine CSEM data

Yutaka Sasaki[1]
[1]Kyushu University

SUMMARY

We present an anisotropic 3D inversion algorithm for marine controlled-source electromagnetic (CSEM) data with the assumption that electrical anisotropy is represented by the vertical and horizontal resistivities. For such anisotropic media, the horizontal and vertical electric fields are related to the horizontal and vertical resistivities, respectively. In addition, as is well-known for magnetotelluric data, the horizontal electric field is insensitive to thin, horizontal resistors associated with the presence of hydrocarbon reservoirs. Thus, the horizontal electric field contributes mainly to defining the horizontal resistivity of the background media, but not resolving thin resistors in the vertical resistivity. As a result, the resolution of marine CSEM data to thin resistors is lower in anisotropic media than that for the isotropic case, unless the possible relationship between the two resistivities is accounted for. We demonstrate using a synthetic example that one can improve the resolution to deep thin resistors significantly in both the vertical and horizontal resistivities by incorporating the equality of the two resistivities into the inversion process. We also show that using multiple-frequency data is important in improving the target and overall resolution.

Keywords: 3D inversion, anisotropy, TIV, marine CSEM

S2-07

Towards quantitative resolution analysis of 3-D EM inversion results. Efficient calculation of the Hessian matrix of frequency-domain EM data misfit using adjoint sources approach

Alexey Kuvshinov[1] and Oleg Pankratov[2]
[1]Institute of Geophysics, ETH Zurich, Switzerland
[2]IZMIRAN, Russian Academy of Sciences, Troitsk, Moscow region, Russia

SUMMARY

We discuss in this abstract an efficient computation of the Hessian matrix of EM data misfit based on adjoint sources approach. We consider this work as a step to the development of quantitative resolution schemes in electromagnetic (EM) frequency-domain problems based on analysis of an inverse of the Hessian matrix. In addition to being the carrier of resolution information the Hessian can be interpreted as an inverse of a posterior model covariance matrix. This interpretation provides a way for better regularization of the inverse problem. We state that using adjoint sources approach one can calculate the Hessian matrix for a price of $O(N)$ forward problem calls per frequency and polarization, where N stands for dimension of model parameter space. Thus this approach allows for substantial computational savings during Hessian computation compared to brute-force approach (numerical differentiation) which requires $O(N^2)$ forward problem calls per frequency and polarization. Moreover adjoint sources approach allows for *exact* estimation of the elements of Hessian matrix, which is not the case if *approximate* brute-force numerical differentiation is invoked.

Keywords: 3-D EM inversion, resolution analysis, Hessian matrix, regularization, adjoint sources approach

S2-08

Resolution of full waveform inversion using controlled-source electromagnetic exploration

Naoto Imamura[1], Tada-nori Goto[1], Junichi Takekawa[1] and Hitoshi Mikada[1]
[1]Kyoto University

SUMMARY

A 3D full waveform inversion method is presented using a controlled-source electromagnetic (CSEM) method. We demonstrate that conductive anomalies around subsurface could be estimated from data simulated for a synthetic model. We discuss the resolution of our CSEM inversion method, in terms of the distribution and the orientation of dipoles of transmitter and receivers. We considered two cases in the alignment of x-oriented receiver and transmitter dipole arrays: (i) 2D inline alignment of the arrays, and (ii) pseudo 3D parallel offset alignment. Our synthetic inversion examples show that the latter could lead to the resolution of results higher than the former, in particular deeper part of our subseafloor model. We then confirmed that the utilization of tricomponent transmitters and receivers could give better locations both in horizontal and vertical directions in inversion results than that of x-oriented dipoles only. These differences of the inversion results could be explained by the distribution of electric flux and charge around the boundary of conductive anomalies. We would like to conclude, from these results, that it would be essential to consider the deployment of multicomponent transmitter and receivers whose arrays are aligned in 3D for reliable inversion.

Keywords: marine CSEM, FDTD, full waveform inversion

S2-09

Enhancing Resolution of 3D-EM Inversion Models through a Co-operative Approach

Michael S.G. McMillan[1], and Douglas W. Oldenburg[1]
[1]University of British Columbia, Geophysical Inversion Facility. Vancouver, B.C., Canada

SUMMARY

We present a method for co-operatively using multiple electromagnetic (EM) datasets to produce a consistent three-dimensional resistivity inversion model with improved resolution. Both field data from the Antonio gold deposit in Peru, and synthetic data are used to demonstrate this technique. We first separately invert airborne time-domain EM (AEM), controlled source audio-frequency magnetotellurics (CSAMT) and time-domain pole-dipole direct current resistivity (DC) field measurements to recover 3D resistivity models. Each inversion recovers a large resistor related to gold hosted silica alteration. Collectively they map a resistor location that is in reasonable agreement with its known outline, as drawn from geologic drill logs. Variations between the 3D models exist, and this motivates a subsequent co-operative method in which the AEM resistivity model is used as a reference model for a joint inversion of the CSAMT and DC data. The 3D co-operative result appears to define the target resistor with greater precision than the individual inversions, and additionally it highlights small conductive zones of potential interest within the resistive region. Synthetic modeling of the same three data sets over a simulated resistivity distribution further demonstrates that the co-operative approach qualitatively and quantitatively improves the accuracy of the resulting inversion model in the target area.

Keywords: co-operative inversion, forward modeling, airborne-EM, CSAMT, DC resistivity

S2-10

New Advances for a joint 3D inversion of multiple EM methods

Naser Meqbel[1] and Oliver Ritter[1]
[1]GFZ German Research Centre for Geosciences, Potsdam, Germany

SUMMARY

Electromagnetic (EM) methods are routinely applied to image the subsurface from shallow to regional structures. Individual EM methods differ in their sensitivities towards resistive and conductive structures as well as in their exploration depths. Joint 3D inversion of multiple EM data sets can result in significantly better resolution of subsurface structures than the individual inversions. Proper weighting between different EM data is essential, however. We present a recently developed weighting algorithm to combine magnetotelluric (MT), controlled source EM (CSEM) and DC-geoelectric (DC) data. It is well known that MT data are mostly sensible to regional conductive structures, whereas, CSEM and DC data are more suitable to recover more shallow and resistive structures. Our new scheme is based on weighting individual components of the total data gradient after each model update. Norms of each data residual are used to assess how much weight individual components of the total data gradient must have to achieve an equal contribution of all data sets in the inverse model. A numerically efficient way to search for appropriate weighting factors could be established by applying a bi-diagonalization procedure to the sensitivity matrix. Thereby, the original inverse problem can be projected onto a smaller dimension in which the search of weighting factors is numerically cheap. We demonstrate the efficiency of the proposed weighting schemes and explore the model domain with synthetic data sets.

Keywords: 3-D forward modelling, Inversion, Joint Inversion.

S2-11

Tailored fit-for-purpose 3D interpretation of marine CSEM data

Max A. Meju[1]
[1]Petronas Carigali, Kuala Lumpur, Malaysia

SUMMARY

Three-dimensional 3D surveying has now emerged as the method of choice in marine controlled-source electromagnetic (CSEM) exploration for hydrocarbons, but there are limitations in the way that field data are currently interpreted. A major challenge is how to consistently interpret data from 3D surveys to recover the correct physical parameters (specifically, the lateral limits, depth location and electrical resistivity) of potential hydrocarbon-saturated reservoirs in the presence of complex geological overburden. Here, a simple tailored approach is proposed for effective interpretation of CSEM survey data, made possible by 3D edge-detection attributes analysis and accurate background resistivity determination. The determination of the exact background resistivity at each receiver location facilitates the assessment of near-surface heterogeneity and burial-depth of significant resistors, while the use of edge-detection attributes helps constraint the lateral limits of potential 3D resistors, such that a 'fit-for-purpose' iterative inverse modelling approach can be used to improve the constrained estimation of subsurface targets and the assessment of model uncertainty on simple computational platforms. This approach is demonstrated using CSEM survey data from a deepwater fold-and-thrust belt setting.

Keywords: Marine CSEM interpretation, exact background resistivity, 3D edge-detection attributes, tailored inverse modeling, case study

S2-12

A framework for three-dimensional coupled seismic-electromagnetic inversion

G. A. Newman[1], E. Um[1] and M. Commer[1]
[1]Lawrence Berkeley National Laboratory, Berkeley CA USA 94720

SUMMARY

We present a three-dimensional (3D) coupled seismic-electromagnetic (EM) imaging workflow and apply it to subsalt exploration. Our coupled seismic-EM imaging workflow is characterized as follows. First, seismic data are transformed into the Laplace domain. Because the transformation changes the modeling of seismic fields from wave to diffusion, seismic and EM data are governed by the same physics of diffusion. Accordingly, seismic and EM resolutions are better matched, leading to robust coupling of velocity and resistivity models via structural constraints and petrophysical methods. Second, we separate the full joint seismic-EM inversion into three simple inversion components: seismic inversion, EM inversion and cross-gradient inversion for structure. This separation helps us mitigate non-convergence issues that frequently arise when an objective function of the joint inverse problem has multiple data, regularization terms and constraints. The cross-gradient inversion and resistivity-velocity cross-plots are used to infuse structural information from velocity to resistivity models and vice versa as described below.

Keywords: 4-6 keywords, coupled seismic-EM inversion, cross gradients, sub-salt exploration, matched resolution

Programming in 3-D electromagnetics: look from outside

Alexey Geraskin
Earthquake Research Institute, University of Tokyo

SUMMARY

For the last few decades incredible progress in the area of computer science has been achieved both in hardware and software developments. Software development by itself has become a standalone and very complex science. Programming technologies went far away from the early times and continue to progress very rapidly. Nowadays these technologies make it possible to develop software much more efficiently and in general without pain and frustration. On the other hand, a progress in EM forward and inverse modelling of the 3-D problems with realistic levels of complexity and spatial detail is still not satisfactory. Still computational loads to tackle realistic scenarios appear to be prohibitively demanding due to memory and speed limitations. And very often such limitations are caused not only by hardware deficiency, or/and inefficiency of the used numerical algorithms, but also by immaturity of the codes which implement these algorithms. Author's analysis of some 3-D EM codes led him to conclusion that most of them are substantially out-of-date and written in a rather inefficient and naive way. This causes not only the serious performance issues, but also makes existing codes very difficult to understand, maintain, and introduce new features. In this abstract some ideas about modern efficient coding are discussed.

Keywords: computer science, effective programming, parallel computations, optimization, refactoring

S3-02

Monitoring Concepts Using Borehole Transient Electromagnetic and DC Resistivity Methods: 3D Simulation Studies for the Effective Detection of CO_2 Leakages

Jana Börner[1], Martin Afanasjew[1,2], Felix Eckhofer[2], Julia Weißflog[1], and Klaus Spitzer[1]
[1]Institute of Geophysics and Geoinformatics, [2]Institute of Numerical Analysis and Optimization
Technical University Bergakademie Freiberg

SUMMARY

We present a feasibility study for a 3D-time-lapse electromagnetic monitoring concept combining surface direct current (DC) resistivity and borehole transient electromagnetic (BTEM) measurements. The early detection of CO_2 leaking from underground storages into shallow aquifers is a major safety issue. Since electric conductivity is highly sensitive to the presence of CO_2 within water-bearing porous media, geo-electromagnetic methods provide an easy-to-apply, non-invasive and cost-effective way of monitoring large-scale targets.

To understand the petrophysical background, we have developed laboratory equipment to quantify the conductivity change arising from dissolving CO_2. The test conditions represent characteristic p/T-scenarios for depths up to 200m. From the data we derive a petrophysical model to predict the conductivity contrast. Based on this, 3D numerical simulation studies show how to design a well-performing monitoring arrangement. We propose the combination of the DC resistivity and the BTEM method with complementary sensitivity patterns to enhance the subsurface resolution.

Our simulation studies are carried out using state-of-the-art in-house software developed by our working group. The governing partial differential equations are discretized using higher-order Lagrange and Nédélec finite element formulations on unstructured grids giving excellent flexibility with respect to arbitrary model geometry. The time domain problem is particularly demanding. To reduce the numerical effort we have developed Krylov subspace techniques in both the time and frequency domains.

Keywords: forward modeling, finite elements, borehole transient electromagnetics, DC resistivity, CO_2 leakage detection

S3-03

The potential of magnetotelluric using for reservoir monitoring

Ronghua Peng[1], Xiangyun Hu[1], Yunxiang Liu[2], Zhangxiang He[2]
[1]China University of Geosciences, Wuhan, China
[2]BGP Inc., China National Petroleum Corporation

SUMMARY

Reliable monitoring of subsurface changes is critical for engineering and environmental surveillance. Information about fluid redistribution in the subsurface is key element for effective management in reservoir production. Electromagnetic inductive methods particularly the CSEM methods have gained much attention and much effort has been put to its feasibility and reliability for monitoring in land and offshore reservoir over last several years. While few considers magnetotelluric techniques (AMT/MT) which employs natural sources for this purpose. Here, we conducted a series of numerical experiments to investigate the potential of magnetotelluric for land reservoir monitoring. 3D forward modeling demonstrates that time lapse changes in MT responses are small but measurable with required prior information and careful analysis. Additionally, through the analysis of derivatives of time lapse MT responses, we are able to accurately locate the oil-water contact within the reservoir during its production. The image derived from derivatives of MT responses at different production stages of the same depleted zone demarcate the areal extent of injected fluid and highlight the flooding front during production.

Keywords: magnetotelluric, 3D forward modeling, reservoir monitoring, flooding front location

S4-01

Three-dimensional inversion of small-loop electromagnetic data: Water leak detection in an artificial sandy ground

Kyubo Noh[1], Yonghyun Chung[1], Soon Jee Seol[1], Joongmoo Byun[1], and Toshihiro Uchida[2]
[1]Hanyang University, Department of Natural Resources and Geoenvironmental Engineering, Seoul, Korea
[2] National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan

SUMMARY

Small-loop electromagnetic (EM) data measured in a multi-dimensional geometry have been commonly interpreted by using piece gathered images obtained from one-dimensional (1D) inversion techniques. However, mis-interpretation can arise from 1D-based techniques due to the three-dimensional (3D) nature of the subsurface conductivity distribution. In this study, in order to avoid such potential mis-interpretation, we adopted 3D interpretation techniques for a water leak detection scenario. An artificial sandy ground was constructed to simulate water leaks in three different stages and broadband EM signals were measured using a GEM-2 sensor. Various numerical experiments were systematically conducted using synthetic data sets which are calculated for the synthetic resistivity models reflecting the real test site prior to the inversion of field data. Numerical experiments showed that the proper application of *a priori* information as constraints could enhance the imaging capability. Especially, structural boundaries which are incorporated in the roughness matrix make the interfaces between background soil and filled sands more distinct. Consequently, the successful 3D inversion of field data showed that water leakage could be visualized by small-loop EM data if we apply the 3D inversion technique with the careful selection of *a priori* information as constraints.

Keywords: 3D inversion, Small-loop EM, *a priori* information, Water leak detection

S4-02

Transient electromagnetic survey on the Araba fault, Jordan: A 3D conductivity model

Annika Rödder[1,2] and Bülent Tezkan[1]
[1]Institute of Geophysics and Meteorology, University of Cologne, Albertus-Magnus Platz, 50923 Köln, Germany
[2]Institute of Geosciences, Johann-Wolfgang-Goethe University, Altenhoeferallee 1 60438 Frankfurt am Main, Germany

SUMMARY

72 transient electromagnetic soundings using the inloop configuration were carried out perpendicular and parallel to the strike direction of the Araba fault in Jordan. A 50 m x 50 m transmitter loop was used and $\dot{H}x$ and $\dot{H}y$ components of the magnetic field were measured additionally to the $\dot{H}z$ component using a receiver coil constructed at the University of Cologne. However, the multidimensional interpretation of the TEM data was limited to the quantitative modeling of the $\dot{H}z$ component. The late time apparent resistivities derived from the $\dot{H}z$ induced voltages show clear differences between the stations located at the eastern and at the western part of the Araba fault. The fault appears as a boundary between the resistive western (ca. 100 Ωm) and the conductive eastern part (ca. 10 Ωm) of the survey area. On profiles parallel to the strike, late time apparent resistivities were almost constant as well in the time dependence as in lateral extension at different stations, thus indicating a 2D resistivity structure of the investigated area. After having been processed, the data were interpreted by conventional 1D Occam and Marquardt inversion. The 1D models were then used as a starting model for a 2D resistivity forward modeling which was extended to a 3D resistivity model explaining in a satisfactory way the time dependences of the observed transients at all 72 stations. In general, the observed lateral conductivity anomaly associated with the location of the Araba fault indicates the different water contents of the structures west and east of the fault which blockade the groundwater flowing from the mountains to the east of the valley.

Keywords: inloop transient electromagnetics, Araba fault, Jordan, 3D forward modeling

S4-03

Importance of the MT diagonal tensor coefficients for 3D inversion

Sophie Hautot[1] and Pascal Tarits[2]
[1]Imagir, IUEM, Place Nicolas Copernic 29280 Plouzané, France
[2]IUEM, Place Nicolas Copernic 29280 Plouzané, France

SUMMARY

Three-dimensional (3D) inversion of magnetotelluric (MT) data has increased dramatically both in industry and academic projects. Some 3D inversion codes are in use and some are under development. The 3-D inversion of real data showed the difficulty to handle data sets of various quality, distribution and at variable number of frequencies. The results are dependent on data analysis, selection and correction, on the chosen mesh and inversion parameters as well as the data actually inverted. Here we investigate the usefulness of the diagonal terms of the MT tensor in the inversion for different 3D models for which these coefficients are either small or large. We discuss the importance of the error floor threshold of off-diagonal and diagonal coefficients. Finally we emphasis the need of high quality data acquisition and analysis in order to obtain correct estimate of the diagonal coefficients.

Keywords: magnetotellurics, inversion, diagonal tensor coefficients, data analysis

S4-04

3-D Inversion of a 200+ Site Magnetotelluric Array for Deep Geothermal Exploration

Edward Bertrand[1], T. Grant Caldwell[1], Graham J. Hill[1] and Stewart L. Bennie[1]
[1]GNS Science, 1 Fairway Drive, Avalon, Lower Hutt 5010, New Zealand

SUMMARY

To advance understanding of the constraints and mechanisms that control the flow of fluids and heat through the upper crust of the Taupo Volcanic Zone (TVZ), an array of 220 broadband MT measurements were collected from 2009 to 2012. 2-D and 3-D inversion models of subsets of these MT data have shown quasi-vertical, 'plume-like' zones of low resistivity that rise from an inferred magmatic zone below the brittle-ductile transition (~7 km depth) and connect to near-surface geothermal systems. The most plausible interpretation of these low-resistivity zones is that they represent hot-fluids, convectively transporting heat upwards through the brittle crust. While these MT inversion models strongly support the long-standing model of hydrothermal convection in the TVZ, variations between models suggest that heat flow and mass transport is more 3-D than previously thought. While computationally demanding, the 3-D inversion code WSINV3DMT is used to invert subsets of these array MT data.

Keywords: 4-6 keywords, 3-D inversion, geothermal exploration, Taupo Volcanic Zone

Three-dimensional electrical conductivity structure beneath the Philippine Sea using three-dimensional marine MT inversion dealing with topographic effect

Noriko Tada[1, 2], Kiyoshi Baba[2] and Hisashi Utada[2]
[1]Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
[2]Earthquake Research Institute, The University of Tokyo

SUMMARY

We performed three-dimensional (3-D) inversion analysis for a data set of seafloor electromagnetic (EM) survey in the Philippine Sea and in the western edge of the Pacific Ocean. The EM data were obtained using ocean bottom electromagnetometers (OBEMs) at 25 sites. The data obtained have been analyzed based on a magnetotelluric (MT) method. The seafloor bathymetry and land/ocean distribution are known to significantly affect the EM data observed by OBEMs because of high contrast in the conductivity between seawater and crustal rocks. Thus, we have developed new 3-D inversion scheme for marine MT data, which can treat both regional large-scale and local small-scale topography. The best electrical conductivity model shows four features. (1) The conductivity of the Philippine Sea mantle is higher than that of Pacific mantle shallower than 200 km depth, and become almost equal to that of Pacific mantle in deeper parts. (2) A conductive anomaly is located at around 125 km depth beneath the Sikoku and Parece-Vera Basins. (3) A resistive anomaly is located at around 40 km depth beneath the Daito and Oki Daito ridges. (4) A resistive anomaly is located at shallower than 240 km at the northern part of the Shikoku Basin.

Keywords: Marine magnetotellurics, 3-D inversion, Topographic effect, Upper mantle, Stagnant slab

SP1-01

Multi-order Vector Finite Element Modelling of 3D Magnetotelluric Data including complex geometry and anisotropic earth

Aixa M. Rivera-Rios [1], Bing Zhou [2], Graham Heinson [3] and Stephan Thiel[4]
[1]Dept. of Geology and Geophysics, Adelaide University, aixa.rivera-rios@adelaide.edu.au
[2]Dept. of Geology and Geophysics, Adelaide University, bing.zhou@adelaided.edu.au
[3]Dept. of Geology and Geophysics, Adelaide University, graham.heinson@adelaide.edu.au
[4]Dept. of Geology and Geophysics, Adelaide University, Stephan.Thiel@adelaide.edu.au

SUMMARY

We are presenting the progress made on the development of a computational algorithm to model 3D Magnetotelluric data using Vector Finite Element Method (VFEM). The differential equations to be solved are the decoupled Helmholtz equations for the electric field, or the magnetic field, with a symmetric and real conductivity tensor. These equations are defined to include anisotropic earth and complex geometry (such as surface topography, and subsurface interfaces). These governing equations are formulated for the secondary field, where the primary field is the solution of an air domain, homogeneous half-space or layered earth.

This study will compare the effectiveness of two boundary conditions, the Generalize Perfect Matched Layers method (Fang, 1996) versus Dirichlet boundaries. Dirichlet boundary conditions are applied on the tangential fields, assuming that the boundaries lie far away from the inhomogeneities. The Perfect Matched Layer scheme defines an artificial boundary zone that absorbs the propagating electromagnetic fields, to remove the boundary effects. This project will also study the application of a surface boundary in order to remove the air domain, and reduce the model dimension.

In this algorithm, high order edge elements are defined based on covariant projections (Crowley, Silvester, & Hurwitz Jr., 1988) for hexahedral elements. Therefore, vector basis functions are defined for the 12 edges (8 nodes) element, 24 edges (20 nodes) element, and 48 edges (26 nodes) element. By this definition, this vector basis will have zero divergence in the case of rectangular elements and relatively small divergence in the case of distorted elements. They are defined to study their numerical accuracy and speed, and see if the divergence correction is automatically satisfied.

Keywords: 3D forward modeling, vector finite element, MT method, anisotropy

SP1-02

Convergence studies for the finite element simulation of the 3D MT boundary value problem

Antje Franke-Börner, Ralph-Uwe Börner, and Klaus Spitzer
TU Bergakademie Freiberg, Germany

SUMMARY

We present convergence studies for the three-dimensional magnetotelluric boundary value problem. The equation of induction is solved with the help of the finite element method in a bounded domain Ω applying Dirichlet and Neumann boundary conditions. For the model of a homogeneous halfspace, the error of the numerical solution with respect to the analytical solution is considered for a hierarchy of nested unstructured tetrahedral meshes. We examine the convergence behaviour with increasing number of degrees of freedom in dependence of the order p of the finite elements ($p = 1, 2, 3$), the frequency f of the electromagnetic fields ($f = 0.01, 0.1, 1$ Hz), and the mesh refinement strategy applied. If the true solution is unknown, convergence studies are performed using the numerical finest-grid solution for comparison. These studies are subsequently used to evaluate the quality of different formulations of the three-dimensional magnetotelluric boundary value problem that arise from Maxwell's equations. Exemplarily, the equation of induction is derived in terms of the magnetic field, the electric field, the magnetic vector potential and the electric scalar potential as well as the anomalous magnetic vector potential. Our computations illustrate that the convergence behaviour varies with the conductivity distribution in the model. Furthermore, global convergence results do not necessarily apply to local convergence, e. g., at arbitrary data points on the earth's surface. We finally demonstrate the merit of convergence studies for the estimation of the accuracy of the numerical solution for a close-to-reality model of Stromboli volcano.

Keywords: magnetotellurics, finite element method, boundary value problem, 3D, numerical simulation

SP1-03

Finite element 3D Modeling of Geoelectromagnetic Fields for Controlled and Natural Sources

Marina G. Persova[1], Yuri G. Soloveichik[1], Marina G. Tokareva[1], Petr A. Domnikov[1], Denis V. Vagin[1] and Tatiana G. Shashkova[1]
[1]Novosibirsk State Technical University, Russia

SUMMARY

In this work the approaches to the finite element 3D-modeling of geoelectromagnetic fields in time and frequency domains when they are excited by the controlled sources as well as in the magnetotelluric sounding tasks are described. The presented approaches are based on the use of the vector finite element method on the optimized hexahedral irregular meshes (with the eliminated "unnecessary" nodes) and the technology of two-stage and multistage field separation. The technology of two stage field separation is based on the field separation of the horizontally layered medium with the solution of one three dimensional task for calculating the additional field of all 3D objects simultaneously, and the technology of multistage field separation is based on the successive calculation of the additional fields of 3D objects (one by one). When modeling in the time domain the approximation of time derivative is performed with the use of the three-layer implicit finite-difference scheme with the changing time steps. The approaches presented are implemented in the software system with the use of parallelism. The examples of the tasks solutions and the computational costs for different geoelectrical models and the sources of electromagnetic field excitation are given.

Keywords: forward 3D-modeling, finite element, magnetotellurics, transient electromagnetic

SP1-04

Efficient Three-Dimensional Time Domain TEM Simulation Using Finite Elements, a Nonlocal Boundary Condition, Multigrid, and Rational Krylov Subspace Methods

Martin Afanasjew[1], Ralph-Uwe Börner[2], Michael Eiermann[1], Oliver G. Ernst[1], and Klaus Spitzer[2]
[1]Institute of Numerical Analysis and Optimizaion, TU Bergakademie Freiberg, Germany
[2]Institute of Geophysics and Geoinformatics, TU Bergakademie Freiberg, Germany

SUMMARY

We present a numerical method for the simulation of transient electromagnetic fields (TEM) in arbitrary three-dimensional conductivity distributions. The focus lies on models with an isolating air half-space, a model class that is of great importance in many applications. Our method allows us to restrict the computational domain to the subsurface by modeling the effect of the air half-space in terms of a nonlocal boundary condition at the air-earth interface. The spatial discretization is done using the finite element method employing Nédélec elements on an unstructured tetrahedral grid. Rational Krylov subspace methods in conjunction with a geometric multigrid method are used on the resulting linear system of ODEs to advance an initial electric field to selected times of interest. We present a number of standard models. The obtained results clearly show the reduction in computational effort compared to previous implementations.

Keywords: finite element method, Krylov subspace, nonlocal boundary condition, time domain, transient EM

SP1-05

Three-dimensional transient electromagnetic simulation using Rational Krylov subspace projection methods

Ralph-Uwe Börner[1], Oliver G. Ernst[2], Stefan Güttel[3]
[1]TU Bergakademie Freiberg, Germany, Institute of Geophysics and Geoinformatics
[2]TU Bergakademie Freiberg, Germany, Institute of Numerical Analysis and Optimization
[3] University of Manchester, UK, School of Mathematics

SUMMARY

The rapid inversion of 3-D electromagnetic (EM) measurements to obtain maps of the electrical conductivity of subsurface regions of interest remains one of the major computational challenges of geoelectromagnetic prospecting. The forward simulation step, in which the response of a given conductivity distribution is computed, remains a key element in the inversion process, since it must be carried out multiple times for each inversion. The availability of fast forward modelling codes is therefore of crucial importance.

The discretization of Maxwell's equations in the time and frequency domain yields linear algebra problems that can be formulated in terms of matrix functions $f^\tau(\boldsymbol{A})\boldsymbol{b}$ with $f^\tau(z) = \exp(\tau z)$ and $f^\tau(z) = (z-\tau)^{-1}$, respectively. In our application, where the problem size N is very large, it is not possible to compute the dense matrix $f^\tau(\boldsymbol{A})$ explicitly.

We will consider approximation methods for these matrix functions, which avoid the computation of large matrix functions and directly compute approximations to the vector $f^\tau(\boldsymbol{A})\boldsymbol{b}$ by projection on low-dimensional subspaces.

We will show numerical examples and compare our results in terms of numerical accuracy and efficiency.

Keywords: forward modeling, time-domain, finite elements, Krylov subspace method

SP1-06

Three dimensional modeling of controlled-source electromagnetic response for inductive and galvanic components

Seyedmasoud Ansari[1], and Colin G. Farquharson[1]
[1]Memorial University of Newfoundland, St. John's, Canada

SUMMARY

We deal with the 3D finite-element forward modeling of CSEM problems in the frequency domain. To better appreciate the physical behavior of the EM fields and to improve the speed of the solution process both the Helmholtz diffusion equation and the equation of conservation of charges are considered here. A decomposition of the electric field into vector and scalar potentials is performed. Using the Galerkin finite-element method both edge and nodal element basis functions are used to form the discretized system of equations. Unstructured tetrahedral elements are used to grid the computational domain. The system is solved for a number of examples, most importantly: for the galvanic scenario where a line source of current excites a relatively conductive prism buried in a half-space model, and for a classic inductive example where a transmitter loop passes over a model of large conductivity contrast. For the example presented here, the solution from our code is in a good agreement with the data given by the integral-equation method. The inductive and galvanic parts of the electric field are also simulated. The CSEM response for the presented example is significantly affected by the contribution from the galvanic part.

Keywords: finite-element, forward modeling, unstructured mesh, CSEM, inductive and galvanic parts.

SP1-07

Forward modeling for CSEM excited by the cable current with finite length

Takao Koyama[1]
[1]Earthquake Research Institute, University of Tokyo

SUMMARY

In this paper, we developed a new modelling code for the controlled source electromagnetic (CSEM) method, in which the current source of a line element with finite length is implemented. We choose an approach by the integral equation method and the 2-D FFT for horizontal plane and variable separation for both vertical components of the locations at the source and the receiver are adapted to reduce both computational memory and time. To evaluate the electromagnetic (EM) fields excited by a line source with finite length, the source term in wavelength domain for the horizontal plane is input analytically in the code. To accelerate the convergence of numerical solution of integral equation, modified IDM is adapted as a pre-conditioner to solve a huge linear equation. By numerical test, the results by our code with a line source with a unit length show good coincidence with the results by other codes with a dipole source, and the accuracy of our codes are confirmed. Further, in our code, not only single line element but also several line elements can be input. Thus by superposing the several short line elements, the EM fields can be calculated, excited by a cable source with arbitrary shape. Further, a vertical line sources can be also input in our code.

Keywords: forward modeling, modified IDM, CSEM method, line element with finite length

Three-dimensional electromagnetic modeling study of sea and topography effects on EM field induction by grounded electrical source airborne transient electromagnetics (GREATEM) system surveys

Sabry Abd Allah[1], Toru Mogi[1] and Elena Fomenko[2]

[1]*Institute of Seismology and Volcanology, Hokkaido University, N10W8, Kita-ku, Sapporo 060-0810,*
[2]*Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, Moscow, Russia*

SUMMARY

The GREATEM survey was carried out at an alluvial plain, Kujukuri beach, central Japan where sedimentary rocks and shallow water prevail. The results from this survey were remarkable in that a reliable resistivity structure was obtained to a depth of 300-350 m both on land and offshore and low resistivity structures prevail both on land and offshore (Ito et al, 2011). Another GREATEM survey was carried out at northwestern Awaji Island, where granitic rocks crop out onshore. From this survey, an underground resistivity structures to a depth of 1 km onshore and to a depth of 500 m offshore were revealed by this survey. The results showed that the absolute resistivity value onshore was much lower than the exited survey results. To circumvent this problem and understanding the reason for an inaccurate results, we used the 3D EM modeling scheme based on the staggered grid finite difference (FD) method (Fomenko and Mogi, 2002) to study the sea effects on electromagnetic field (EM) induction using GREATEM system surveys at coastal areas with topographic features. The models consisted of two adjacent layers of different conductivity, where the sea is thin sheet of a good conductor placed on top of a uniform half space earth medium. The EM responses are calculated for different positions of grounded electrical source (10, 20 and 300m) from coastline in landward and the uniform half space earth medium resistivity vary from resistive host rock 100ohm-m to high conductive host rock 1 ohm-m.

The results have shown that, the sea effect on EM field induction by GREATEM system surveys depend on the ground electrical source position from coastline, for example the sea effect in case of the source positions are 10m or 20m from coastline (Awaji Island case) is much higher than the case where the source position is 300m from coastline (Kujukuri beach case). Furthermore, the sea effect is a function of the host rock resistivity, for example in case the host rock resistivity is 100 ohm-m, the effect of sea on EM field is higher than the both case of the host rock resistivities are 10 and 1 ohm-m.

Keywords: Airborne EM, Sea effect, 3D resistivity modeling, GREATEM survey, Coastal areas survey.

SP1-09

3D finite-difference time-domain forward modeling with convolutional perfectly matched layers (CPML) absorbing boundary condition for marine CSEM

Zhou Xiaochen[1], Hu Xiangyun[1], Han Bo[1]
[1]Institute of Geophysics and Geomatics, China University of Geosciences, Wuhan, China

SUMMARY

Marine CSEM surveying has been viewed as a new exploration technology for mapping offshore hydrocarbon in recent years. To interpret the received signals correctly, we need new forward modeling and inversion tools. This paper has developed 3D finite-difference time-domain (fdtd) forward modeling codes with the convolutional perfectly matched layers (CPML) absorbing boundary condition to reduce the error of numerical solutions. We compare numerical solution to semi-analytic solution for a 1D model to provide a self-check on the fdtd solution in 2000 m deep waters. The agreement between numerical solution and semi-analytic solution proves the viability and validity of the fdtd codes. Then we simulate electric field responses of a 3D model in the same water depth as 1D model. 3D numerical experiment shows that we can identify the 3D reservoir boundaries with amplitudes and phases information. However, the characters of boundaries become hard to confirm when frequencies are gradually increasing. We also find phase responses are more sensitive than amplitudes responses when anomalous body is presenting, which is in according with plane-layered modeling. Hence phase responses are very useful in marine CSEM explorations. In conclusion, this paper focuses on high accuracy of numerical solutions and may have great impact on 3D survey planning, imaging, data processing, and inversion.

Keywords: marine CSEM, finite-difference time-domain (fdtd), forward modeling, convolutional PML

SP1-10

Rigorous interpolation near interfaces in 3D finite-difference EM modeling

Daniil V. Shantsev[1], and Frank A. Maaø[2]
[1]EMGS, Trondheim, Norway
[2]Statoil, Trondheim, Norway

SUMMARY

We present a rigorous method for interpolation of electric and magnetic fields close to an interface with a conductivity contrast. The method takes into account not only a well-known discontinuity in the normal electric field, but also discontinuity in all the normal derivatives of electric and magnetic tangential fields. The proposed interpolation method is applied to marine 3D controlled-source electromagnetic modeling where sources and receivers are located close to the interface between conductive seawater and resistive formation. It is shown that for the finite-difference time-domain method based on the Yee grid, the interpolation error at the interface can dominate the numerical dispersion error in a broad range of cell sizes. The error is dramatically reduced if the proposed interpolation scheme is used. The proposed interpolation operators can have arbitrary length and can handle either uniform or non-uniform grids as well as arbitrary orientation of the interface with respect to the grid.

Keywords: forward modeling, interpolation, marine CSEM, finite difference, discontinuity

SP1-11

Speeding up a marine 3D CSEM code with GPU

M. Sommer[1], S. Hölz[1], M. Moorkamp[2], A. Swidinsky[1], B. Heincke[1], C. Scholl[3] and M. Jegen[1]
[1]GEOMAR, Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1-3, 24148 Kiel, Germany
[2]University of Leicester, Department of Geology, University Road, Leicester, LE1 7RH, UK
[3]Fugro, Fugro Electro Magnetic GmbH, Wolfener Strasse 36V, 12681 Berlin, Germany

SUMMARY

One main problem in 3D time domain controlled source electromagnetic (CSEM) inversion is the high runtime of forward modeling codes. We reduced the runtime of the 3D time domain finite difference CSEM code TEMDDD by the GPU-parallelization of expensive algorithms. The code solves the electromagnetic diffusion equation by discretization of spatial operators and subsequent calculation of eigenpairs. These eigenpairs are found by approximation of the eigenspace in a Krylov subspace using the Spectral Lanczos Decomposition Method. This algorithm was not parallelizable in its original form due to implementation of the surface boundary condition. We show for the marine case that replacing the original boundary condition at the air-sea surface by a discretized air layer allows GPU parallelization of every time consuming algorithm of the code. Speedups between 20 to 60 have been achieved compared to the original code for a large 3-D model. Currently, we are developing a 3D-inversion based on this code.

Keywords: forward modeling, marine CSEM, GPU

SP1-12

3D modeling of fractional diffusion to describe electromagnetic induction in fractured geological media

Jianchao Ge[1], Mark E. Everett[1] and Chester J. Weiss[2]
[1]Department of Geology and Geophysics, Texas A&M University
[2]Department of Geosciences, Virginia Tech University

SUMMARY

The fractional diffusion of the electromagnetic (EM) induction in fractured media is modelled using the 3D finite difference (FD) method in frequency domain. The EM fractional diffusion is one subset of anomalous transport processes, which is usually induced by the heterogeneities with various scales in the media. The governing equation of this process is based on the classical Maxwell equation and modified according to the continuous time random walk (CTRW) theory. The roughness parameter β in the new equation is directly related to the degree of heterogeneity of formations. To access the performance of this theory, the 3D FD modelling experiments are developed. The calculated EM response of a 1D layered model is compare with the analytical solution to validate the accuracy of the code. Then the FD solution to a homogenous model containing a 3D rough faulting zone is calculated to compare with responses to several classical diffusion model (with β=0). The comparable classical models are expected to obtain to explore the relationship between the roughness β with the heterogeneities of the media.

Keywords: 4-6 keywords, forward modeling, inversion, finite element, marine CSEM, case study

SP2-01

Mapping 3-D mantle electrical conductivity from space. Development of a new 3-D inversion scheme based on analysis of matrix Q-responses

Christoph Püthe and Alexey Kuvshinov
Institute of Geophysics, ETH Zürich, Switzerland

SUMMARY

We present a novel 3-D frequency domain inversion scheme to recover 3-D mantle conductivity from satellite magnetic data, e.g. provided by the forthcoming *Swarm* mission. The scheme is based on an inversion of matrix Q-responses (Q-matrices), which relate external (inducing) and internal (induced) coefficients of the spherical harmonic expansion of the time-varying magnetospheric field. This concept overcomes the problems associated with source determination inherent to recent schemes based on direct inversion of internal coefficients. Matrix Q-responses are estimated from time series of external and internal coefficients using iteratively re-weighted least squares and period averaging. A gradient-type frequency domain inversion scheme has been developed to deal with matrix Q-responses. In order to make the inversion tractable, we elaborated an adjoint approach to compute the data misfit gradient and parallelized the numerical code with respect to frequencies and elementary sources, which describe the external part of the magnetospheric field. The inversion scheme has been verified by computing Q-matrices for a given 3-D conductivity model and subsequently recovering this model from the data.

Keywords: 3-D inversion, mantle conductivity anomalies, multivariate analysis, Q-matrix

SP2-02

Bootstrapping as a means of uncertainty analysis in inversion modelling of magnetotelluric data

Sebastian Schnaidt[1,2,3] and Graham Heinson[1,2]
[1]Discipline of Geology and Geophysics, The University of Adelaide, Australia
[2]Deep Exploration Technologies Cooperative Research Centre
[3]sebastian.schnaidt@adelaide.edu.au

SUMMARY

Many geophysical models are created without any form of uncertainty analysis. Mainly because it is not easy to produce a meaningful uncertainty analysis from a single best fit model. Most geophysicists are aware of the limitations of their model, but if the model is passed on to a third party, this information is lost and the risk of misinterpretation arises, which can have serious consequences. We use the bootstrapping resampling method to create reduced data sets from the base data set by random omission of data points. Each of these new data sets is then run through a conventional inversion process to produce an ensemble of solutions with minor variations. The ensemble creation stage is followed by an appraisal stage of statistical analysis of the solution ensembles to infer an uncertainty estimate for the models based on that data set, to increase the reliability of the modelling process. The last step of the workflow is the visualisation and communication of the results to experts as well as non-experts. We demonstrate the effectiveness of the technique with a case study on a magnetotellurics data set from the Southern Delamerian transect in Victoria, Australia. The process yields a clear and easy to interpret uncertainty map for the connected model.

Keywords: Bootstrapping, inversion modelling, solution ensemble, uncertainty analysis, magnetotellurics

SP2-03

3D inversion of magnetotelluric phase tensor and apparent resistivity & phase data with ModEM and its application to a 250-site MT array data set from the San Andreas fault, California

Kristina Tietze[1], Oliver Ritter[1], Gary Egbert[2]
[1]German Research Centre for Geosciences GFZ, Potsdam, Germany
[2]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, USA

SUMMARY

With advancing computational resources, three-dimensional (3D) inversion techniques have become feasible in recent years and are now a more widely used tool for magnetotelluric (MT) data interpretation. Galvanic distortion caused by small-scale near-surface inhomogeneities of dimensions remains an obstacle for 3D MT inversion which so far has experienced little attention. If not considered properly, the effect on 3D inversion can be immense and result in erroneous subsurface models and interpretations. To tackle the problem we recently implemented inversion of the distortion-free phase tensor (Caldwell et al. 2004) into the ModEM inversion package (Egbert & Kelbert 2012). We tested the new inversion using synthetic and real-world data sets. The dimensionless phase tensor components describe only variations of the conductivity structure. When inverting these data, particular care has to be taken of the conductivity structure in the a priori model, which provides the reference frame when transferring the information from phase tensors into absolute conductivity values. Our results obtained with synthetic data show that phase tensor inversion can recover the regional conductivity structure in presence of galvanic distortion if the a priori model provides a reasonable assumption for the regional resistivity average. We also used phase tensor inversion for a data set of more than 250 MT sites from the central San Andreas fault, California, where a number of sites showed significant galvanic distortion. We find the regional structure of the phase tensor inversion results compatible with previously obtained models from impedance inversion. In the vicinity of distorted sites, phase tensor inversion models exhibit more homogeneous/smoother conductivity structures.

Keywords: magnetotellurics, 3D inversion, phase tensor, galvanic distortion, static shift

SP2-04

An approach for the three-dimensional interpretation of MT data distorted by the sea- and static effects

Tae Jong Lee[1], Jihyang Choi[1], Junmo Yang[2], Seong Kon Lee[1], In-Hwa Park[1] and Yoonho Song[1]
[1]Korea Institute of Geoscience and Mineral Resources
[2]Korea Institute of Nuclear Safety

SUMMARY

Three-dimensional (3D) magnetotelluric (MT) surveys were performed from 2004 to 2006 in Jeju Island to figure out any possible structure or potential anomaly related with remnant deep geothermal resources. To solve the old question that both the induction vectors and 3D inversion results have indicated the existence of a conductive anomaly in central parts of the island, 3D inversion incorporating the static shift was applied with the sea-effect-corrected MT data. The sea-effect was excluded from the Jeju MT dataset by an iterative correction method. The method repeats correction of sea effect by putting 3D forward models both including and excluding the surrounding sea effect as the components of the tensor distorted by the sea effect and then inverting the sea-effect-corrected responses. 3D inversion in this study dealt with the static shifts as inversion parameters. Reconstructed images using the MT dataset with sea-effect correction showed the conductive anomaly in a similar depth to previous works and RMS misfits converged to a lower value than those of inversion using non-corrected MT dataset. There can be big possibility of the isolated conductive anomaly under the Jeju Isalnd. Further investigations are needed to see if it is from a fracture containing saline water or from features related to old volcanic activities.

Keywords: magnetotelluric, sea-effect, static shift, 3D interpretation, Jeju Island

SP2-05

Removable of galvanic distortion on 3-D MT inversion.

Masanori Tani[1], Hitoshi Mikada[1], Tada-nori Goto[1], Junichi Takekawa[1] and Weerachai Siripunvaraporn[2]
[1]Kyoto University, [2]Mahidol University

SUMMARY

Recent years, three-dimensional magnetotelluric (MT) inversion is widely used in geophysical structural surveys. In this paper, we show how to galvanic distortion would influence to 3-D MT inversion results, and would like to propose an improvement of model covariance matrix which could deal the galvanic distortion. For accommodating the galvanic distortion effects, we first simulate a set of synthetic MT response for some models and then add the distortion effects that are a function of observation locations. We applied WSINV3DMT as an inversion method to these synthetic MT responses. As a result, we confirmed distinct differences between 3-D MT inversion results depending on the degree of galvanic distortion. When we applied WSINV3DMT with the modified model covariance matrix, we obtained better inversion result. Based on these numerical experiments, we conclude that the galvanic distortion should be considered and be dealt with in the inversion.

Keywords: 3-D magnetotelluric, Inversion, Galvanic distortion

SP2-06

Inverse modelling of 3D Controlled-Source Electromagnetics using a Parallel Discrete Adjoint method

Oscar Peredo, Vladimir Puzyrev, Jelena Koldan, Guillaume Houzeaux, Mariano Vázquez, Josep de la Puente, José María Cela
Barcelona Supercomputing Center, Computer Applications in Science and Engineering department
Repsol-BSC Research Center

SUMMARY

Supercomputers are tools for the simulation of complex processes that require a very large number of operations to be solved in a reasonable time. This technological devices have forced the application experts to adapt themselves to the new way of designing computers and have motivated the development of parallel versions of their algorithms using specific well-proven programming models. In this context, our aim is to explore EM inverse problem resolution, using PDE-constrained optimization algorithms that can exploit the features of the current technologies and be able to adapt to future trends. The discrete adjoint method also known as *first discretize-then optimize* is a versatile and powerful technique to obtain gradients in this kind of problems. It is based on the resolution of an adjoint linear system using information from the discretized PDE. This property motivates its study and implementation using a legacy parallel PDE solver in order to profit from the parallelization scheme already implemented in it. First we will explain the technical details of the discrete adjoint method, and then we will show how to apply it to an EM forward model based in secondary potentials.

Keywords: parallel computing, inversion, discrete adjoint method, CSEM

SP2-07

Inversion of large scale airborne time domain electromagnetic data

Christoph Schwarzbach and Eldad Haber
University of British Columbia, Vancouver, Canada

SUMMARY

3-D inversion of airborne electromagnetic data is, to date, a challenging computational problem. The size of the survey area in relation to the desired spatial resolution of subsurface electrical resistivity as well as the mesh size that is required to adequately discretize all transmitters and receivers give rise to very large meshes. Solving the forward problem repeatedly on such a mesh either requires intense computational resources or is simply infeasible. However, using a single mesh for both the inverse problem and the forward problem for all transmitters is not necessary. The forward problem for a single source or a small group of sources can as well be solved on a much smaller mesh which only needs to be fine close to the selected transmitters and receivers. Away from transmitters and receivers the mesh can be coarse. The forward problem is, thus, broken into a number of smaller problems which are easier and faster to solve. In this paper, we present an implementation of this idea using a finite volume discretization on OcTree meshes. We demonstrate our approach with a synthetic example involving 4064 transmitters.

Keywords: forward modeling, inversion, finite volume, airborne EM

SP2-08

3-D Inversion of Helicopter Electromagnetic Data

M. Scheunert[1], M. Afanasjew[2], R.-U. Börner[1], M. Eiermann[2], O. G. Ernst[2], and K. Spitzer[1]
[1]Institute of Geophysics and Geoinformatics
[2]Institute of Numerical Analysis and Optimisation
TU Bergakademie Freiberg (Germany)

SUMMARY

Helicopter electromagnetic (HEM) measurements allow to manage huge surveys in a very short time. Due to the enormous data and model sizes, laterally constrained 1-D inversion schemes for the entire surveys are still state of the art, even for those parts of the survey where 3-D conductivity anomalies are expected.

We present the framework of an inversion scheme capable of revealing an anomalous three-dimensional conductivity structure in the subsurface for parts of the survey where 3-D conductivity anomalies are expected. For solving the inverse problem, we apply a straightforward Gauss-Newton method and a Tikhonov-type regularization scheme. The derived linear least squares problem is solved with Krylov subspace methods, such as LSQR, that are able to deal with the inherent ill-conditioning. We reformulate the discrete forward problem in terms of the secondary electric field, employing both finite difference and finite element methods. The resulting systems of linear equations subsequently yield expressions for the gradient and approximate Hessian of the minimization problem. Resulting from the unique transmitter-receiver relation of the HEM problem, an explicit representation of the Jacobian matrix is used. To handle the sensitivity related quantities, a tensor-based problem formulation is exploited.

For application studies we consider a 3-D model problem as published by Siemon, Auken, and Christiansen (2009) using a finite difference discretization. We present first inversion results for synthetic data with a noise level of up to 5%.

Keywords: HEM, 3-D inversion, explicit Jacobian, FD and FE, Gauss-Newton

SP2-09

Regularization for 3D DC resistivity inversion

Felix Eckhofer[2], Julia Weißflog[1], Ralph-Uwe Börner[1], Michael Eiermann[2], Oliver G. Ernst[2], Klaus Spitzer[1]

[1]Institute of Geophysics and Geoinformatics
[2]Institute of Numerical Analysis and Optimisation
TU Bergakademie Freiberg (Germany)

SUMMARY

We present current research associated with a common project of the TU Bergakademie Freiberg and the Deutsches Geoforschungszentrum Potsdam (GFZ). The aim of this project is to exploit the distinct sensitivity patterns of different EM methods to enhance the resolution.

Here, we focus on the DC resistivity method. We have reimplemented our finite element secondary field DC forward modeling approach on unstructured grids and proved its theoretical convergence rate of $\mathcal{O}(h^2)$.
To stabilise the inversion procedure and provide additional information to avoid ambiguities, a suitable regularization strategy is necessary. We have implemented a smoothness regularization in which the penalty function measures the norm of a weak gradient of the conductivity field. It is implemented using a mixed finite element method with Raviart-Thomas elements on unstructured grids.

Preliminary tests using a synthetic conductivity model and a small number of electric sources yield promising results in view of the inversion of real DC resistivity data sets.

Keywords: 3D DC resistivity, mixed finite element methods, regularization

SP2-10

Gauss–Newton Inversion Algorithm to Estimate Resistivity Parameter Using a Dual-Optimal Grid Approach

Agah D. Garnadi[1] and Hendra Grandis[2]
[1] Dept. Mathematics, Faculty of Mathematics and Natural Sciences, Institut Pertanian Bogor, Jl Meranti Kampus Darmaga, Bogor 16680, Indonesia. E-mail: agah.garnadi@gmail.com
[2] Dept. Geophysics, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia. E-mail: grandis@earthling.net

SUMMARY

RESINVM3D is an open source 3-D, MATLAB based, resistivity inversion package. The inversion algorithm employs the Gauss-Newton method to achieve balance between efficiency and robustness. To solve the forward problem, the package uses finite volume method. In this work, we study the use of optimal grid in the package to achieve numerical accuracy to suppress numerical error.

Keywords: Resistivity estimation, optimal grid, Finite-Volume inversion, three-dimensional (3-D).

SP2-11

Three-dimensional inversion for transient electromagnetic sounding technologies with loop source and for induced polarization using finite element approximation

Marina G. Persova[1], Yuri G. Soloveichik[1], Marina G. Tokareva[1], Petr A. Domnikov[1], Michael V. Abramov[1], Denis V. Vagin[1] and Eugenia I. Simon[1]
[1]Novosibirsk State Technical University, Russia

SUMMARY

This work presents the approaches to the three dimensional inversions for transient electromagnetic sounding technologies with the loop source and for induced polarization (IP). The approaches to the three dimensional inversions for transient electromagnetic soundung technologies are based on the two stage procedure, which includes the stage of starting model building with the use of cell structures and the stage of more precise definition of parameters of local three dimensional heteroginities, extracted from the cell structures. The latter is performed with the use of the total non-linear 3D inversion. In doing so at the first stage the fields of separate cells influence are calculated by solving a linearized forward problem and at the second stage it is done by finite element 3D modelling with the use of vector basic functions. The approaches to the three dimensional inversions for the induced polarization technologies are based on the iterative procedure where each iteration consists of two stages: the search for chargeability (limited polarizability) and the search for decay function parameters. Here the geoelectrical fields are also calculated with the use of the finite element method (FEM). The proposed approaches were tested on the synthetic data which were obtained by means of 3D modelling for different geoelectrical models. The results of the test showed that the developed approaches make it possible to find distribution of conductivity and polarizability in the three dimensional medium adequate to real models.

Keywords: 3D-inversion, finite element, transient electromagnetic, induced polarization

SP3-01

Automatic detection and classification of induction anomalies in helicopter-borne electromagnetic data sets

Angelika Ullmann, Bernhard Siemon, and Marion Miensopust
Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover

SUMMARY

Helicopter-borne electromagnetic (HEM) surveys reveal the spatial conductivity distribution in the subsurface. For instance, they are applied to groundwater or mineral exploration. As the HEM footprint, i.e., the lateral resolution capability of the HEM system, is rather small, smooth conductivity structures are close to 1-D settings and 1-D inversion of HEM data is widely used. However, conductivity structures with strong lateral variations (induction anomalies) are not reproducible by standard 1-D inversion procedures and require multidimensional modeling. Thus, the information where such induction anomalies occur in a HEM data set is crucial. Since HEM surveys accumulate huge amounts of data, an automated detection of these anomalies is preferable. We present a new search algorithm for identification, selection, classification, and extraction of induction anomalies in HEM data sets. 2-D grids of the logarithmic apparent resistivities are produced and utilized as input for several image processing methods to extract the induction anomalies present. The identified induction anomalies are classified using region-based shape descriptors which are known from image processing. The search algorithm is tested on a case study on real HEM data.

Keywords: Helicopter-borne electromagnetics, induction anomalies, image processing, buried valley

SP3-02

3D 'Tau' imaging of subsurface conductors by contemporary helicopter borne time domain EM systems

Saurabh K. Verma[1]; Toru Mogi[2]; Sabry Abd Allah[2]; Shashi P. Sharma[3]; Elena Fomenko[4]
[1]NGRI, Hyderabad, India
[2]ISV, Hokkaido University, Sapporo, Japan
[3]IIT Kharagpur, Kharagpur, W Bengal, India
[4]Moscow State University, Moscow, Russia

SUMMARY

The 'Tau' parameter, governing the decay behavior of measured transients in the time domain EM methods, represents a combination of the conductivity and size parameters of subsurface conductors. 'Tau' imaging as a function of time describes the depth-wise variations while their values along various profiles provide clues towards the spatial distributions of geological conductors. 3D 'Tau imaging' thus can provide useful information on the subsurface distribution and disposition of various conductors. In this paper we evaluate the efficacy of two generically different helicopter TEM systems, namely, those flying the transmitter loop during the survey and the system employing a grounded transmitter cable ('GREATEM' system), in providing realistic 3D 'Tau' maps describing distribution of subsurface geological conductors. It is found that the mode of primary field excitation in the two systems plays an important role in the resulting 'Tau' images.

Keywords: Helicopter TEM methods, 'GREATEM' system, 'Tau' imaging of HTEM data

SP3-03

Robust processing of onshore controlled-source electromagnetic data from a three-phase galvanic source

Rita Streich[1,2], Michael Becken[3], and Oliver Ritter[1]
[1]GFZ German Research Centre for Geosciences
[2]Now at Shell Global Solutions International
[3]University of Münster

SUMMARY

High-quality data is key to any meaningful inversion. Whereas robust processing techniques are routinely used for estimating high-quality magnetotelluric (MT) transfer functions, such techniques are not commonly applied for controlled-source electromagnetic (CSEM) processing, although CSEM and MT data exhibit similar noise characteristics. We have implemented a new CSEM processing scheme that combines CSEM-specific preprocessing and statistically robust least-squares stacking to extract interpretable ground responses from noisy CSEM data. We apply this processing scheme to signals from a new CSEM transmitter that is equipped with three grounded electrodes and allows us to generate signals at multiple source polarizations with relatively little field effort. For this transmitter setup, we can formulate a bi-variate relation between the source currents injected through any two of the source electrodes and the recorded EM field components. This leads to an over-determined system of equations that includes all available data from multiple source polarizations and is solved for the ground responses in a robustly weighted least-squares sense. This process also provides error estimates that are directly fed into subsequent 1D and 3D inversion. We demonstrate the retrieval of CSEM responses from data recorded in an area heavily affected by various sources of strong cultural noise, including cathodic protection systems, wind power plants and major power lines.

Keywords: land CSEM, processing, robust statistics

SP3-04

Downward-continued pseudo resistivity section using normalized full gradient (NFG) in VLF-EM method

Daisuke Hyodo, Hitoshi Mikada, Tada-nori Goto and Junichi Takekawa
Kyoto University

SUMMARY

Electromagnetic waves with monochromatic or band-limited signals from VLF transmitters would generate secondary induced components of magnetic field due to buried electrical conductivity contrasts. The method, so-called VLF-EM, has been a powerful tool for mapping subsurface geological structures or buried artificial objects because of the cost-effectiveness and of the handiness of surveys that uses only receivers. However, it has not been tested to estimate a pseudo-resistivity section, both the apparent resistivity and the depth of conductive anomaly by using the measured magnetic components with a single frequency. In this study, we introduced the Normalized Full Gradient (NFG) method, generally used for the downward continuation of the potential filed data, for estimating the location and the apparent resistivity in the subsurface using the magnetic components of the secondary induced on the surface. We first simulate a VLF-EM data set for a 2D synthetic model. The cross section of NFG values derived from horizontal component of magnetic field clearly indicates high peaks at edges of a zone of low resistivity anomaly buried in the subsurface. The peak of NFG values from vertical component corresponds with the centre of the anomaly. We then estimated a pseudo-section of apparent resistivity from the VLF-EM data as weighted by the NFG values at each depth. We confirmed that the weighted apparent resistivity takes lower values in the vicinity of the low resistivity anomaly than in the surrounding area, although the estimated value is a little higher than the original. We would like to conclude that our simple technique could give approximate subsurface resistivity structures readily than in the current practice of VLF-EM. Our method could provide an initial model of three-dimensional inversion and would be useful for further geological interpretations.

Keywords: VLF-EM method, potential field, downward continuation, NFG, apparent resistivity

SP4-01

Telluric method of natural field induced polarization

Nikita Zorin and Andrey Yakovlev
Moscow State University, Moscow, Russia

SUMMARY

Conventional induced polarization (IP) methods are very useful in shallow exploration, but may become a considerable challenge (especially in difficult areas) when the depth of interest exceeds 50 - 100 meters, making it necessary to work with significant dipole separation and cumbersome power source. Therefore there was always a great interest in extracting information of IP from magnetotellurics (MT) data, now giving rise to a new branch of Low Frequency EM called Natural Field Induced Polarization (NFIP). The major challenge of NFIP is how to distinguish the weak IP anomaly from the strong EM noise caused by inductive effects in the medium. It is shown below, that for getting best results one should use electric (telluric) components of the MT field, namely the ratio of the electric field at a survey point to the reference electric field at some remote site (i.e. components of so-called *telluric tensor*). Over a non-polarizable medium under certain conditions and at a sufficiently low frequency phase of the ratio is directly proportional to frequency, and magnitude is almost frequency-independent. Application of the formulas that take into account these features of telluric field allows to significantly attenuate inductive noise and to extract the IP response from both phase and absolute value of telluric tensor (TT) components.

The proposed approach was tested on a number of 2D and 3D models; numerical experiments showed reliable results. At present we are working on development of the theoretical basis and application area of the method, adjustment of the operational frequency band etc. It is also planned to carry out a series of experiments to apply the approach to real field data.

Keywords: induced polarization, natural field, natural source, magnetotellurics, modeling, Cole-Cole

SP4-02

Three-dimensional simulation of the electromagnetic fields induced by tsunamis: A case study for the 2011 Tohoku Tsunami

Luolei Zhang, Hisashi Utada, Hisayoshi Shimizu, Kiyoshi Baba, Takuto Maeda
Earthquake Research Institute, University of Tokyo, Tokyo, Japan

SUMMARY

The motion of seawater induces electromotive force of significant intensity due to Faraday's law, and resulting electromagnetic field can be recorded by instruments installed on land or at ocean bottom. However, a few studies were successfully simulating motionally induced electric and magnetic fields by an exact and accurate application of Maxwell equations. We built an accurate scheme for numerical simulation to calculate EM fields due to ocean tidal flow, and tested the accuracy by using the source currents in the ocean as expected from a Tohoku Tsunami simulation. The source current distribution is predicted by the flow data calculated by a tsunami simulation in 2-D Cartesian coordinates based on the linear long-wave theory. From the calculated source currents, the three components of magnetic variations were estimated by the forward code. We compared the calculated magnetic field with that observed in response to the devastating Tohoku tsunami of 2011 not only on land observatories but also at some seafloor sites, to check the accuracy of the code. It shows that our results are in good agreement with observations. We also get some characteristics of different components of magnetic field on the seafloor.

Keywords: 3-D forward calculation, tsunami, magnetic field, earthquake

SP4-03

Case study of three-dimensional geotechnical evaluations for tunnel design and construction by helicopter-borne geophysical survey

Kenji Okazaki[1], Yoshihiko Ito[1], Toru Mogi[2], Hisatoshi Ito[3], Youichi Yuuki[4] and Akira Jomori[5]
[1]Civil Engineering Research Institute for cold region, Sapporo, Hokkaido, Japan
[2]Hokkaido University, Sapporo, Hokkaido, Japan
[3]Central Research Institute of Electrical Power Industry, Abiko, Chiba, Japan
[4]Oyo Co., Saitama, Japan
[5]Neo Science Co., Sennan, Osaka, Japan

SUMMARY

Helicopter-borne electromagnetic surveys using a grounded electric dipole source was conducted to delineate resistivity structures in deeper parts of a tunnel construction site in Hokkaido pref., Japan. The survey area is mainly composed of Cretaceous sedimentary rocks, with serpentinite dykes intruded into the sedimentary rocks. The surveys covered the tunnel site and its surroundings, as the three-dimensional information, to estimate the distribution of sediment rocks and serpentinite. As a result, the resistivity structure of deep sections delineated the serpentinite and their distribution, which are useful in understanding potential geotechnical issues when excavating a tunnel.

Keywords: case study, civil engineering, tunnel construction, helicopter-borne geophysical survey

SP4-04

Three-dimensional modeling of frequency-domain helicopter-borne electromagnetic data: A case study of the Cuxhaven Valley

Marion P. Miensopust, Bernhard Siemon and Angelika Ullmann
Federal Institute for Geosciences and Natural Resources, Geozentrum Hannover, Germany

SUMMARY

Helicopter-borne electromagnetic data sets are commonly interpreted using one-dimensional modeling and inversion tools. In many cases this approach is valid (e.g., horizontal layered targets and groundwater applications) but there are areas of higher dimension that are not recovered correctly applying 1D methods. Such an area is the Cuxhaven Valley in northern Germany, which was carved by the melt-water flow after the Elster glaciation. Focused 3D modeling and inversion is required to improve the imaging of the resistivity structure of this complex geological unit. Synthetic tests using a simplified model showed that effects of 1D inversion of data from a 3D structure can be found in the vertical section across the Cuxhaven Valley assembled of 1D inversion models. On the other hand more complex synthetic models are required to explain the real data observed at the valley. The work presented here shows first systematic tests and preliminary results of 3D modeling.

Keywords: helicopter-borne electromagnetics, frequency domain, forward modeling, case study, Cuxhaven Valley

SP4-05

3D inversion of land-based CSEM data from the Ketzin CO_2 storage formation

Alexander Grayver[1], Rita Streich[1,2] and Oliver Ritter[1]
[1]GFZ German Research Center for Geosciences
[2]Now at Shell Global Solutions International

SUMMARY

We present 3D inversion of land CSEM data collected across the CO_2 storage test site at Ketzin, Germany. A newly developed Gauss-Newton type parallel distributed inversion scheme, which is based on a direct forward solver, is applied to recover subsurface conductivity images. Cumulative sensitivity volumes computed for the sparse CSEM survey geometry indicate reasonable spatial coverage along the main survey line. We fit the data to an uncertainty level obtained from robust data processing, and achieve a reasonable fit for most of the receivers. The principal features in the obtained 3D resistivity model are robust against the inversion parameterization and correlate well with the main geological units.

Keywords: land CSEM, 3D inversion, Gauss-Newton, case study

SP4-06

Integrated Geophysical tools for Hydrocarbon exploration in Nile delta area, Egypt

Younis, A.[1,*], EL-Qady, G.[1], Abdalla, M. A.[1], Abdel Zaher, M.[1], khalil, A. E.[2] and Al Ibiary, M. G.[2]
[1] National Research Institute of Astronomy and Geophysics, Helwan, Egypt, abdougeoman@yahoo.com
[2] Geology Department, Faculty of Science, Helwan University, Helwan, Egypt, aminwej@gmail.com

SUMMARY

The Nile Delta Basin offshore Egypt has long been known as a significant source of gas and oil. The study area is located on the Middle Eastern part of the Nile Delta near to Mansoura city. Electromagnetic methods have emerged as promising tools for oil exploration than any other geophysical technique. Hydrocarbon reservoirs typically exhibit higher electromagnetic resistivity than their surroundings. In this study both time-domains electromagnetic (TEM) and Magnetotullurics technologies (MT) have been used to measure subsurface resistivity related to hydrocarbon exploration and integrated with seismic data that performed in the same area. A good coherence was found between the electromagnetic and seismic profiles and show that the Hydrocarbon is exiting in the Abu-Madi and Qawasim channel which represent the main gas containing layers in the Nile delta. The depth and extension of these layers were estimated and imaged and the maximum thickness was 4000 m at profile 1 in the northwestern part of the study area.

Keywords: Hydrocarbon exploration, TEM, MT, Nile Delta, Egypt

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SP4-07

A 3D magnetotelluric study of the basement structure in the Mygdonian Basin (Northern Greece) including galvanic distortion correction.

Anna Avdeeva[1,2], Maxim Yu. Smirnov[3], Alexandros S. Savvaidis[4], Marcus Gurk[5] and Laust B. Pedersen[6]
[1] GEOMAR, Germany
[2] now at: University of Leicester, UK
[3] University of Oulu, Finland
[4] Institute of Engineering Seismology and Earthquake Engineering (ITSAK), Greece
[5] Institute of Geophysics and Meteorology, University of Cologne, Germany
[6] University of Uppsala, Sweden

SUMMARY

During 2006 and 2007 a total number of 90 magnetotelluric sites were deployed in the Mygdonian basin (Northern Greece) to examine the basement structure and to give new information about the top-of-basement depth for wave propagation models. Here we use both 2D and 3D inversion to analyze the data and compare the results. Overall, the structure of the basement is fairly well revealed by the data and our 3D inversion with distortion correction demonstrates that galvanic distortion is not a major issue for these data. Furthermore, the models obtained from these inversions agree well and clearly show the depth to the top of the basement. The top-of-basement depths also agree with information from boreholes available in the area, which gives additional confidence in our interpretation.

Keywords: magnetotellurics, inversion, top-of-basement

SP4-08

3-D electrical resistivity models in the Erimo area, southern central Hokkaido

Hiroshi Ichihara[1], Toru Mogi[2], Kengo Tanimoto[3], Yusuke Yamaya[4], Takeshi Hashimoto[2], Makoto Uyeshima[5] and Yasuo Ogawa[6]
[1]Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
[2]Institute of Seismology and Volcanology, Hokkaido University
[3]Formerly Institute of Seismology and Volcanology, Hokkaido University
[4]National Institute of Advanced Industrial Science and Technology (AIST)
[5]Earthquake Research Institute, University of Tokyo
[6]Volcanic Fluid Research Center, Tokyo Institute of technology

SUMMARY

Erimo area, southern central Hokkaido, northern Japan is a geologically attractive area where the lower crustal rocks and mantle rocks are outcropped due to the arc-arc collision between the Northeastern Japan arc and Kurle arc. Because of seawater surrounding the Erimo area, MT impedances and tippers show strong three-dimensionality of resistivity structure. Thus we applied 3-D resistivity inversion method (WSINV3D program). We obtained several models varying rotation azimuth of the impedances, frequency band and a hyper-parameter of the inversion. All the models explain MT impedances including anomalous off-diagonal phases over 90 degrees. Although significantly different resistivity distributions are obtained outside of MT array, they show similar trends of resistivity distribution in the area shallower than 50 km depth. The similarity of resistivity distribution among the inversions with different conditions indicates robustness of the 3-D inversion results. Common features of these resistivity models are as follows: 1) Highly inclined resistive body (>1000 ohm-m) at the east of Hidaka Main Thrust (HMT), 2) Dike-like conductor (<30 ohm-m) beneath the HMT, and 3) An obvious conductive zone beneath the Horoman peridotite area. They will constrain the geological and aqueous fluid distribution beneath the arc-arc collision zone.

Keywords: arc-arc collision, out-of-quadrant phase, Hidaka Collision zone, 3-D inversion

SP4-09

Three-dimensional magnetotelluric survey over Yunodake and Idosawa Faults in Iwaki area, Fukushima Prefecture

Toshihiro Uchida[1] and Takumi Ueda[1]
[1]Geological Survey of Japan, AIST

SUMMARY

We conducted three-dimensional (3D) magnetotelluric (MT) survey over Yunodake and Idosawa Faults in the Iwaki area, Fukushima Prefecture, Japan. Significant ruptures and displacements occurred along these faults by a strong earthquake on April 11, 2011, which was one of large aftershocks of the Great Tohoku Earthquake on March 11, 2011. The purpose of the MT survey was to obtain electrical resistivity structure of the area and to extract anomalous features along the active faults related to displacements due to past and present earthquakes. We carried out MT measurements at 164 stations in 2012, of which 56 stations were by both AMT and MT frequency ranges, while other 88 stations were only AMT. 3D inversions were conducted by using the data of all 164 stations. The study area is mostly underlain by Miocene and Paleogene sedimentary formations, which are underlain by Cretaceous metamorphic and granitic rocks. The Cretaceous formations outcrop in the northern and western parts of the area. Yunodake Fault extends along the boundary between Miocene formation and Cretaceous metamorphic/granitic formations in the north. The 3D resistivity model clearly indicates a resistivity contrast along Yunodake Fault, corresponding low-resistivity Miocene layer and high-resistivity metamorphic/granitic formations. On the other hand, Idosawa Fault is located in Cretaceous metamorphic formations. There is no significant low resistivity anomaly or a resistivity contrast along Idosawa Fault. Thickness of the Miocene/Paleogene sedimentary layers in the center of the survey area is getting larger toward southeast. Depth of Cretaceous metamorphic formation is approximately 600 – 800 m in the southeastern part.

Keywords: magnetotelluric, 3D inversion, Yunodake Fault, Idosawa Fault, Iwaki, Fukushima, Toshoku Earthquake

SP4-10

Three-dimensional Resistivity Imaging beneath the Fold-and-thrust Belt, Ishikari-teichi-toen Fault Zone, Hokkaido, NE Japan

Yusuke Yamaya[1,4], Toru Mogi[2], Ryo Honda[3], Hideaki Hase[4], Atsuo Suzuki[2], Takeshi Hashimoto[2] and Makoto Uyeshima[4]
[1]National Institute of Advanced Industrial Science and Technology (AIST), yamayama@aist.go.jp
[2]Institute of Seismology and Volcanology, Faculty of Science, Hokkaido University
[3]Tono Research Institute of Earthquake Science
[4]Earthquake Research Institute, The University of Tokyo

SUMMARY

A magnetotelluric (MT) survey was performed in the Ishikari lowland region in order to clarify the distribution of fluids beneath the Ishikari-Teichi-Toen active fault zone (ITFZ), which is regarded as the most hazardous inland fault zone in northern Japan. Four components of impedance tensor and two components of magnetic transfer function at 16 frequencies between 40 and 0.00012 Hz at 50 measurement stations were inverted to a 3-D resistivity structure with the aid of the WSINV3DMT code. The inverted structure showed at the shallower part that the conductive layer (<10 Ωm) corresponding to sediments beneath the lowland lies from the surface down to 7 km deep. The resistivity below 7 km shows a regional boundary between the western-northern and southwestern parts. The conductor is found along the ITFZ beneath this boundary in the middle crust. We interpreted this conductor to be a fluid rich zone, acting as a dynamically weakened zone. The conductive body is also found beneath the Shikotsu caldera, implying magmatic fluids ascending from the mantle or a region of partial melt.

Keywords: magnetotellurics, 3-D inversion, active fault, fold and thrust, active volcano

SP4-11

Electrical conductivity structure of the Alpine Fault, New Zealand – a 3D anisotropic problem

T. G. Caldwell[1], W. Heise[1], Y. Ogawa[2], G. J. Hill[1], E. A. Bertrand[1], S. L. Bennie[1], H. M. Bibby[1], and G. R. Jiracek[3]
[1]GNS Science, New Zealand
[2]Tokyo Institute of Technology, Japan
[3]San Diego State University, U.S.A.

SUMMARY

Magnetotelluric (MT) data from the northern half of a 120 km long segment of the Alpine Fault show that an electrically-conductive zone is present at the down-dip extension of the fault. This zone is interpreted to show a zone of ductile shear containing fluid. While the conductive zone is clearly discernible in the MT phase response from the northern part of the fault segment, the phase response is markedly different in the south showing that the conductivity structure must vary significantly along strike.

Keywords: Magnetotellurics, anisotropy, case study

SP4-12

Investigation of the lithospheric structures and North Anatolian Fault Zone underneath the Marmara Sea by 3D Magnetotelluric modeling.

Tulay Kaya[1], Yasuo Ogawa[1], Takafumi Kasaya[2], S. Bülent Tank[1,3], M. Kemal Tunçer[4], Naoto Oshiman[5], Yoshimori Honkura[1], Masaki Matsushima[1], and Weerachai Siripunvaraporn[6]

[1]Tokyo Institute of Technology, Japan
[2]Jamstec, Japan
[3]Bogazici University, Turkey
[4]Istanbul University, Turkey
[5]Kyoto University, Japan
[6]Mahidol University, Thailand

SUMMARY

This study represents the application of 3D electromagnetic method in a nearly closed inland sea. In order to investigate lithospheric scale structures and extension of the North Anatolian Fault (NAF) zone underneath the Marmara Sea, where the next destructive earthquake is expected to occur in northwest Turkey, we deployed long period ocean bottom electromagnetic (OBEM) instruments in the Marmara Sea. The OBEM data were combined with wide-band magnetotelluric (MT) data acquired at land sites around the Marmara Sea. According to the 3D inversion results, a fluid related highly conductive anomaly in electrical resistivity models extends from the crustal to lithospheric depths and merges with the saline fluid and/or melted mantle material beneath the Cinarcik and Imrali Basins in eastern Marmara Sea and to the south of the Central Basin toward the west. These conductive anomalies are surrounded by relatively resistive anomalies. This system, observed previously in the Duzce region on the NAF in east but terminated to the west of the Izmit region, provides an additional constrain on the continuation of the segmentation of the NAF zone from land into the Marmara Sea. Branches of the NAF zone intersect with the resistive-conductive boundaries underneath the Marmara Sea as is on land. This shows segmented feature of the NAF zone on western Turkey. Another significant result of this study is that resistivity variation underneath the Marmara Sea is similar with the Marmara Region. With reference to this, we suggest extension of three tectonic zones from Marmara Region on land into the Marmara Sea.

Keywords: Ocean bottom electromagnetic (OBEM), Marmara Sea, North Anatolian Fault (NAF), 3d modeling, inversion.

SP4-13

2D Inversion of Pelabuhan Ratu Magnetotelluric Data, Indonesia

Febty Febriani[1], Peng H.[1], Chie Yoshino.[1], Katsumi Hattori.[1], Boko Nurdiyanto[2], Noor Effendi[2], Iwan Maulana[2], Suhardjono[2], Prih Hardjono[2], Eddy Gaffar[3]
[1] Chiba University, Japan
[2]Indonesian Geophysical, Meteorological, Climatological Agency (BMKG), Indonesia
[3]Indonesian Institute of Sciences (LIPI), Indonesia

SUMMARY

To identify the underground electrical structure close to Cimandiri fault, Pelabuhan Ratu, West Java, Indonesia, the subsurface structure near Cimandiri fault has been investigated by forty eight magnetotelluric (MT) sites. The MT exploration was carried out during two weeks, from July 27, 2009 to August 8, 2009. The data were distributed along about 13 km x 6.5 km profile. Two-dimensional modelling using the Ogawa and Uchida 2-D inversion has been applied in this research. The data analysis of 2D inversion is now going on and details will be given in our presentation.

Keywords: magnetotelluric, inversion, Cimandiri fault, Indonesia

SP4-14

Heterogeneous resistivity structure around high seismicity regions in Hakone volcano, Japan

Ryokei Yoshimura[1], Yasuo Ogawa[2], Yohei Yukutake[3], Wataru Kanda[2], Shogo Komori[4], Tada-nori Goto[5], Ryou Honda[3], Masatake Harada[3], Tomoya Yamazaki[1], Masato Kamo[1], Yojiro Yasuda[6] and Masanori Tani[5]
[1]Disaster Prevention Research Institute, Kyoto University, Japan
[2]Volcanic Fluid Research Center, Tokyo Institute of Technology, Japan
[3]Hot Springs Research Institute of Kanagawa Prefecture, Japan
[4]Institute of Earth Sciences, Academia Sinica, Taiwan
[5]Graduate School of Engineering, Kyoto University, Japan
[6]Graduate School of Engineering, Tottori University, Japan

SUMMARY

Seismicity around the Hakone volcano was activated just after the arrival of surface waves caused by the 2011 off the Pacific coast of Tohoku Earthquake. Most of these triggered earthquakes had similar distribution to prior occasional swarm activities. In order to image electrical properties around such seismic events, we carried out audio-frequency magnetotelluric (AMT) measurements at 39 sites in December 2011 (Yoshimura et al., 2012). The spatial distribution of the induction vectors and the phase tensor ellipses suggests that conductive bodies may lie beneath the remarkable regions around which the seismicity increased abruptly just after the occurrence of the Tohoku Earthquake.
In this study, we conducted 3D modeling of dense AMT/MT data (Yoshimura et al., 2012; Ogawa et al., 2012), to figure out electrical characteristics around the triggered seismicity. The full components the impedance tensors at 51 sites in total were inverted using the code developed by Siripunvaraporn et al. [2005]. Significant characteristics of the obtained three-dimensional resistivity model are: (1) the most of the triggered earthquakes, which occurred shallower than a depth of 4km, seem to align along resistivity structural boundaries; (2) surface conductive blocks, in which there were very few earthquakes, were observed beneath not only fumarolic areas but geothermal non-active regions.

Keywords: magnetotellurics, three-dimensional inversion, resistivity structure, Hakone volcano, triggered earthquake

SP4-15

Three-dimensional imaging of fluids under the volcanic arc, around Naruko Volcano, NE Japan

Yasuo Ogawa[1], Hiromi Fukino[1], Masahiro Ichiki[2], and Wataru Kanda[1]
[1]Volcanic Fluid Research Center, Tokyo Institute of Technology
[2]Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University.

SUMMARY

We have carried out wideband magnetotelluric measurements in order to map the distribution of fluids and melts under the volcanic arc in the NE Japan around the Naruko volcano. The area has several Quaternary calderas, such as Naruko, Onikobe, Sanzugawa and Mukaimachi calderas. The area has also high shallow seismicity and has one of the largest intraplate earthquakes, M7.0, in 2008 near the Kurikoma volcano. Thus the area is thought as a good test field to study the relation of fluids and volcanoes and intraplate earthquakes. We have 224 sites in total with average site spacing of ~5km. From the three-dimensional modelling we have imaged (1) subvertical conductors which shallows towards the active volcanic zones under Onikobe, Naruko and Sanzugawa calderas, and (2) seismic activities over the resistive zones above the crustal conductors, which implies earthquake triggering by fluid migration into the brittle crust.

Keywords: magnetotellurics, three-dimensional inversion, fluid, volcano, earthquake

SP4-16

Interpretation on Magmatism beneath the Kyushu Subduction Zone with 3D Electrical Resistivity Image

Maki Hata[1], Naoto Oshiman[2], Ryokei Yoshimura[2], Yoshikazu Tanaka[1], and Makoto Uyeshima[3]
[1]Graduate School of Science, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
[2]Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
[3]Earthquake Research Institute, the University of Tokyo, Yayoi 1-1-1, Bunkyo-ku, Tokyo 113-0032, Japan

SUMMARY

Subsurface magmatism in a subduction zone constructs the volcanic edifices. The edifices contribute the disposition of volcanic structures on the Earth's surface in the subduction zone. In subduction zones, oceanic hydrated slabs bring aqueous fluids into the Earth's mantle and release the fluids by dehydration reaction occurring under a certain pressure-temperature condition. This phenomenon plays an important role in the arc magmatism as it triggers partial melting of the mantle. Such partial melting can be affected by the physical heterogeneity of subducting oceanic plates. The island of Kyushu in the Southwest Japan arc lies in a subduction zone, where the Philippine Sea plate (PSP) subducts beneath the Eurasian plate. The PSP in the Kyushu subduction zone consists of three parts: a relatively old slab, a young slab, and a ridge. Many Quaternary active volcanoes occur in the northern and southern Kyushu associated with the two subducting slabs, whereas no volcano occurs in the central Kyushu (the non-volcanic region) associated with the subducting ridge. Here we present 3D electrical resistivity image beneath the entire Kyushu using inverse modeling of the Network-magnetotelluric data. Concerning the magmatism contributing to the volcanoes on the island of Kyushu, we have found two interesting features: conductive anomalies under the volcanoes which converge at deep depths (>100 km) of the backarc in the northern and southern Kyushu; and a different configuration of only the conductive anomaly in the non-volcanic region which extends to shallower underground (<50 km) of the forearc side than in the volcanic regions. Our 3D image detects the two origins of magma sources represented the conductive anomalies in the Kyushu subduction zone. Additionally, the results reveal that the three different types of the subducting PSP slab can affect the volcanism at the northern, central, and southern Kyushu.

Keywords: inverse modeling, Network-MT method, case study, subduction zone, arc magmatism

On elucidation of the regional anomalous phase contained in the Network-MT data in the Chubu district, central Japan

Makoto Uyeshima[1], Satoru Yamaguchi[2], Hideki Murakami[3], Toshiya Tanbo[4], Ryokei Yoshimura[5], Hiroshi Ichihara[6], and Kentaro Omura[7]

[1]Earthquake Research Institute, The University of Tokyo,
[2]Department of Geosciences, Graduate School of Science, Osaka City University,
[3]Department of Applied Science, Faculty of Science, Kochi University,
[4]Tateyama Caldera Sabo Museum,
[5]Earthquake Hazards Division, Disaster Prevention Research Institute, Kyoto University,
[6]Japan Agency for Marine-Earth Science and Technology,
[7]National Research Institute for Earth Science and Disaster Prevention

SUMMARY

We show a result from 3-D inversion of the Network-MT impedance tensors obtained in the Chubu district, central Japan, with the aid of the wsinv3dmt code (Siripunvaraporn et al., 2005). In a wide area facing the Japan sea, anomalous phase (more than 90 degree) was detected in the response functions. In order to stabilize the inversion, we started the inversion with 10% and 20% error floor for the off-diagonal and diagonal elements of the tensor first. This first stage inversion could not explain the anomalous phase. Then, in the second stage, we put 5% error floor both for off-diagonal and diagonal elements. We reached a final model with RMS=2.5, where the phase anomaly was explained by localized and shallow conductive Fukui Plain which faces the Japan Sea. For the other features, along the Noubi Earthquake (M=8.0) seismic fault zone, a shallow and narrow conductive zone was located, and in the mid-crust beneath the zone, a rather resistive layer (higher than 1k Ohm m) was distributed. In addition, a deep seated conductive zone was detected along the Fukui-Gifu boundary (and along the Niigata-Kobe Tectonic (strain accumulating) Zone). The conductive zone indicates existence of dehydration from the Pacific Plate, and may cause the strain rate accumulation.

Keywords: inversion, Network-MT, anomalous phase, case study

SP4-18

Three dimensional modeling of a large scale magnetotelluric data: Final results from 3-D inversion of the US-Transportable Array

Naser Meqbel[1], Gary D. Egbert[2] and Phil E. Wannamaker[3]
[1]GFZ German Research Centre for Geosciences, Potsdam, Germany
[2]CEOAS- Oregon State University, Corvallis, OR, USA
[3]Energy & Geoscience Institute, University of Utah, Salt Lake City, UT, USA

SUMMARY

The northwestern United States accommodates long history of tectonic activities which vary from subduction system associated with modern arc volcanism in the west to the cratonic stabile lithosphere in the east via an extensional regime in-between. With help of 325 long-period MT sites deployed in 2006-2011 in the framework of the Earthscope project we attempt to shed additional light on the recent and ancient tectonic activities of the northwestern United States. With a nominal spacing of ~ 70 km between sites, our study area spans a rectangular region covering most of the NW USA. For the 3-D inversion of Earthscope MT data we used the full impedance tensor and the vertical magnetic field components of the 325 sites and a fine grid with a horizontal resolution of 12.5 km. Here we present our efforts and discuss final results from 3-D inversion of Earthscope long-period MT data. Our preferred 3-D conductivity model reveals regional to "semi-continental" structures located at various depths from middle to lower crust through the upper mantle. The spatial extents of the main resistive and conductive structures vary from a few hundred to several 100's of km. The 3-D conductivity model is dominated by structures which characterize the spatial variations of the subsurface electrical conductivity and reflect the transition from the tectonically active NW Pacific in the west to the more stable North American tectonic plate in the east. Although rapid development of computation resources and the availability of numerical codes make a 3-D modeling of magnetotelluric (MT) a practical tool even on a personal computers, cautions must be taken into account while handling a large scale real data set. In addition to discussing major conductive and resistive features revealed in our 3-D model we also report on model and data resolution studies conducted to better understanding structures obtained in the preferred model.

Keywords: 3-D forward modeling, inversion, US-Transportable Array.

Three-dimensional inversion analysis of seafloor magnetotelluirc data collected in the northwestern Pacific and implications for the source of petit-spot volcanoes

Kiyoshi Baba[1], Natsue Abe[2], Naoto Hirano[3], and Masahiro Ichiki[4]
[1]Earthquake Research Institute, University of Tokyo
[2]Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
[3]Center for Northeast Asian Studies, Tohoku University
[4]Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University

SUMMARY

Petit-spot is young volcanic activity on very old (about 130 Ma) oceanic plate characterized as a clump of small Knolls which erupted strong to moderate alkaline basalt. This volcanic field is associated with neither any plate boundaries nor hot spots. To elucidate the magma generation process of this new-type volcanic activity, marine magnetotelluric (MT) surveys were carried out using ocean bottom electromagnetometers (OBEMs) in May - August, 2005 and in May, 2007 - August, 2008. Total nine OBEMs were deployed and seven of those were successfully recovered with good quality data. We compiled data at two other sites collected in July, 2003 - November, 2004 and analyzed the nine sites data in total in this study. We first estimated a one-dimensional (1-D) electrical conductivity structure model which explains the data of all sites averagely correcting topographic effect on the observed MT responses. Then, we carried out 3-D inversion analysis using the 1-D model as the initial and prior model. The 3-D inversion program that we used is WSINV3DMT (Siripunvaraporn et al., 2005) but modified for seafloor MT data by Tada et al. (2012). The obtained 3-D model shows two distinct features. 1) The lithospheric mantle beneath the petit-spot field at 37.5°N, 149.8°E (Yukawa Knolls) is relatively more conductive than surrounding area. The conductivity is about 0.003 S/m at about 70 km depth. This feature is depicted as thinned resistive layer in the vertical section. 2) High conductivity (~0.1 S m^{-1}) layer at around 200 km depth is not isolated beneath the petit-spot field but rather distribute widely beneath the survey area except for the area to the northwesten area of the Yukawa Knolls. Checker board inversion and forward modeling tests support that these features are reasonably resolved by the data. The above features make us to speculate that the asthenospheric mantle is partially molten and the melt is extracted to the lithosphere (and partly to the seafloor) by the petit-spot activity. The electrical conductivity at 200 km depth can be explained by small fraction of hydrous and carbonated melt on temperature above the solidus of peridotite including H_2O and CO_2.

Keywords: marine magnetotellurics, lithosphere, asthenosphere, petit-spot

SP4

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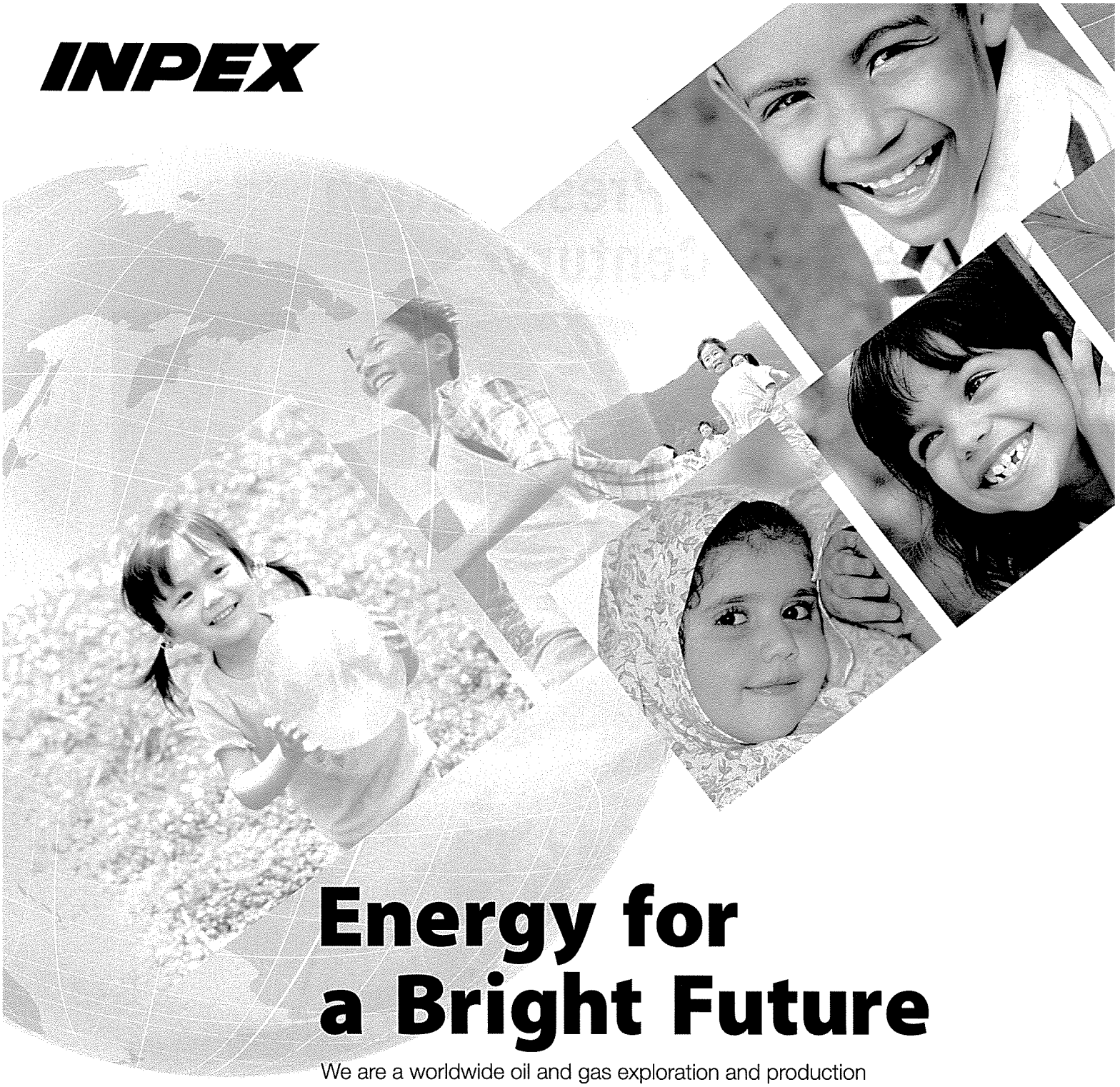

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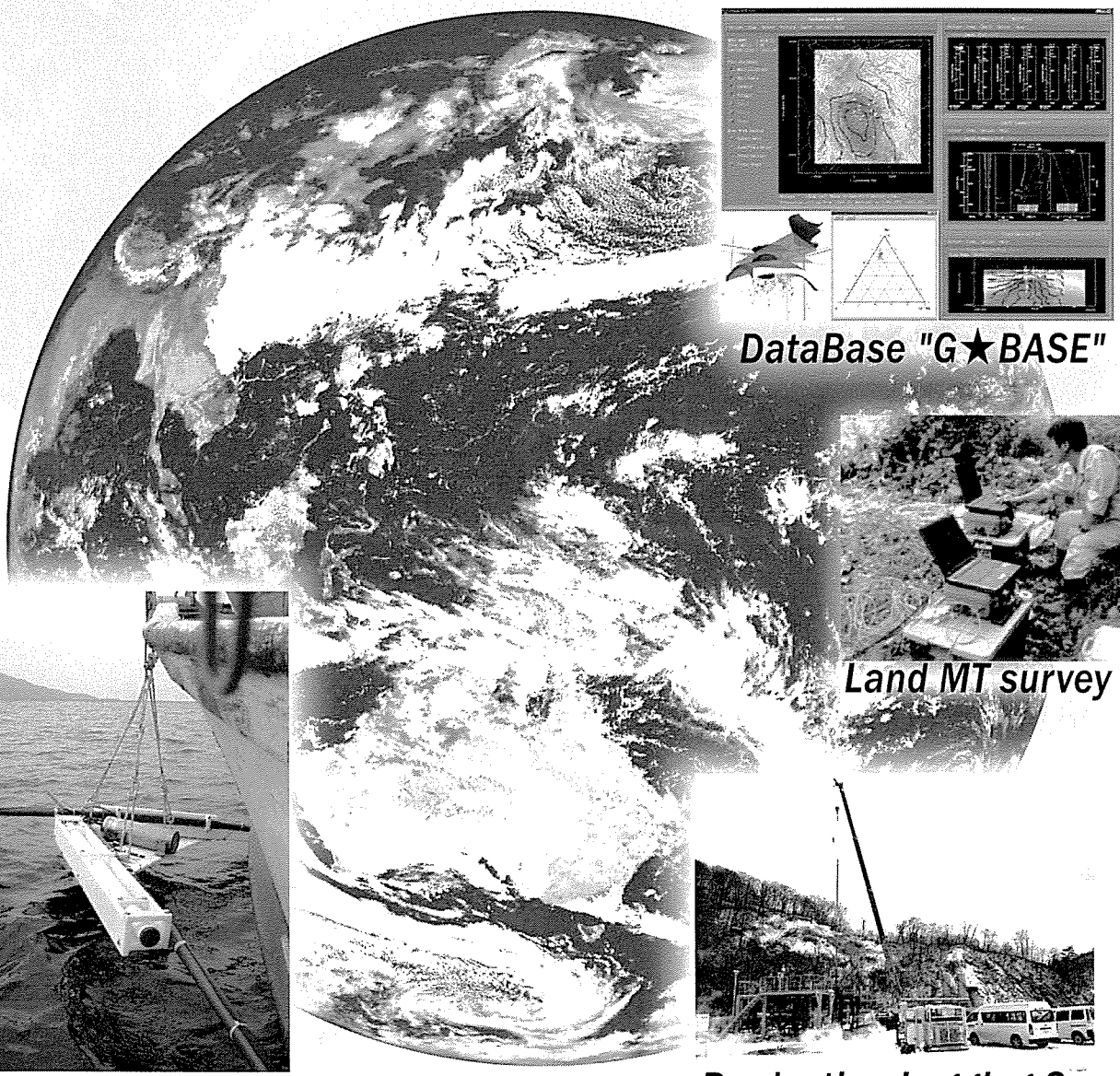

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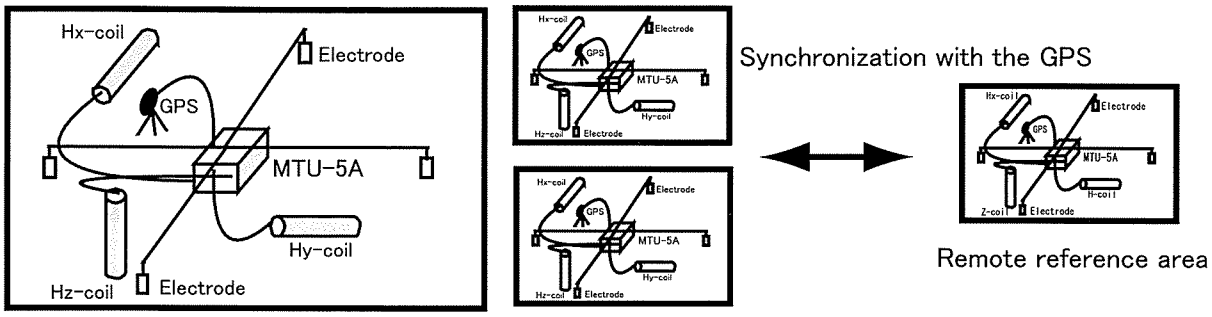

MT/AMT survey measures electric and magnetic field derived by natural electromagnetic wave.

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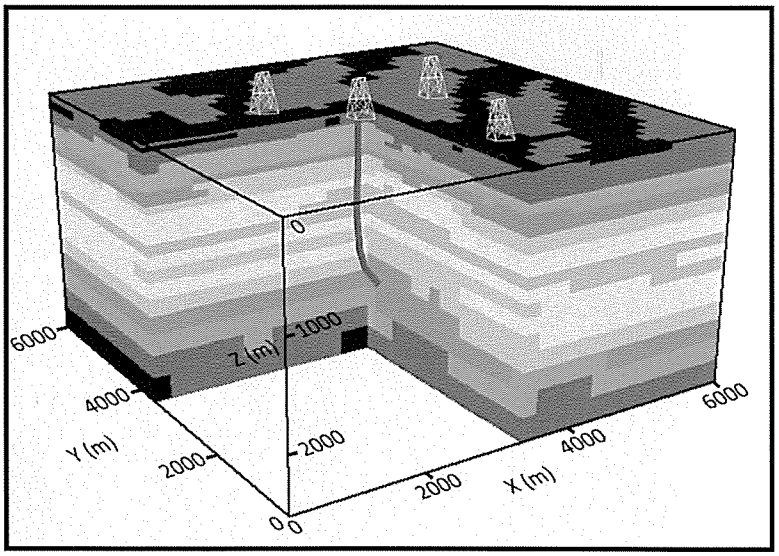

<3D resistivity structure>

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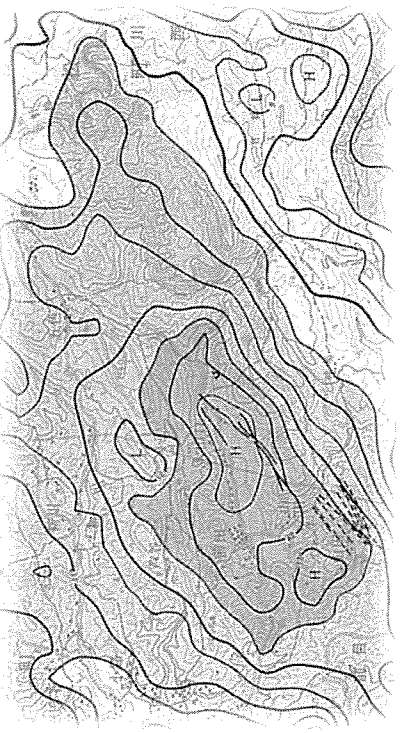

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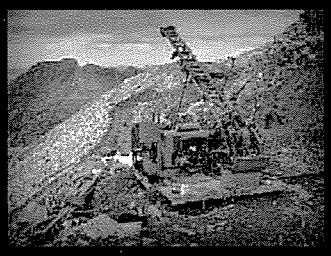

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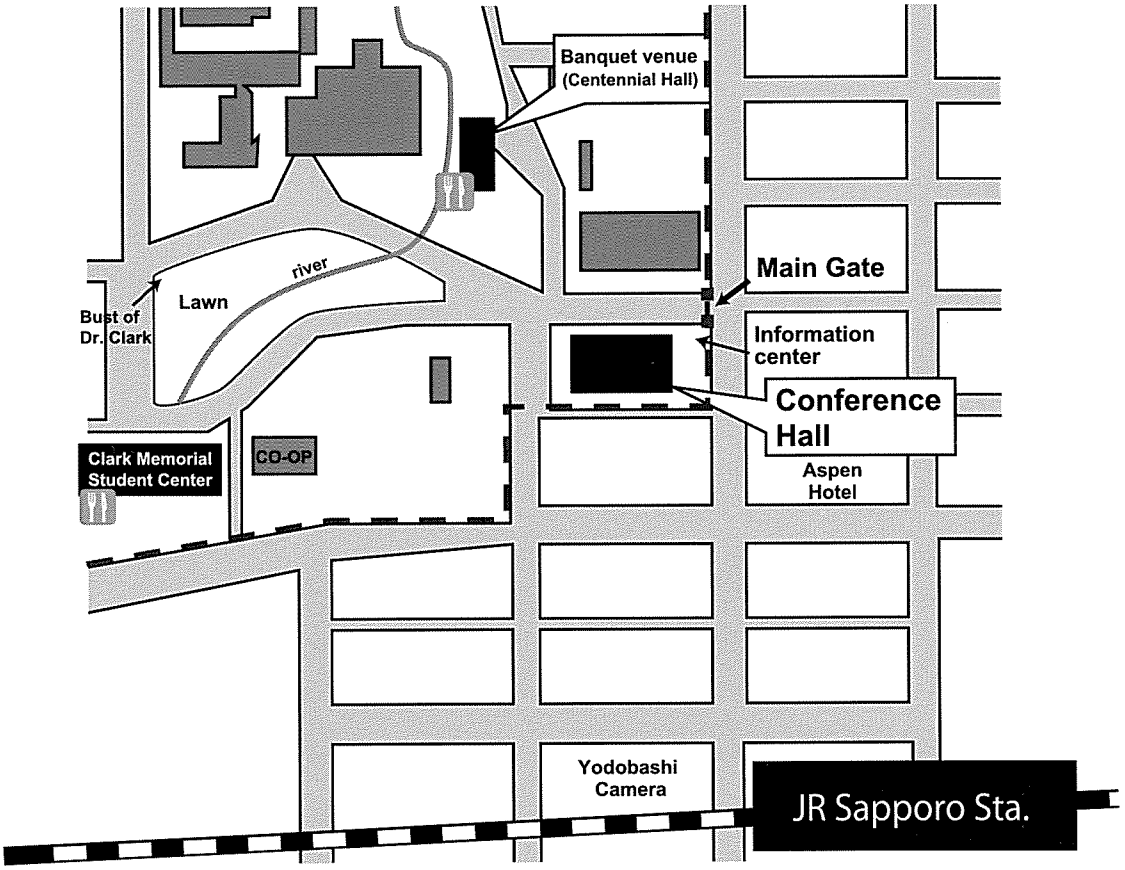

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