Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SMP47-01 会場:203 時間:5 月 22 日 11:00-11:15

火山学と科学掘削
Volcanology and scientific drilling

中田 節也 [1]*
Setsuya Nakada[1]*

[1] 東京大学地震研究所
[1]Earthquake Research Institute, The University of Tokyo

火山の地下構造は，古くから，地表踏査や火山噴出物に含まれる岩片の解析などから推定されてきた。世界的には，まれに，古い火山の地下構造が浸食されて 1km 以上の高度差で露出することもある。しかし，そのような火山の地下構造の化石からは，現在活動的な火山のマグマの通路・蓄積場所や温度構造などについての生の情報を得ることはできない。地球物理学的な探査手法（地震波速度構造，電磁気構造，重力分布，宇宙線透視法による密度解析など）で火山の大まかな地下構造モデルを得ることはできる。しかし，それらの手法によって得られる情報には，解析精度や推定されたものの実体に関する問題があり，地下物質の構造や物性などについての詳細な情報を得ることはできない。掘削によって，火山の地下の物質を得るとともに，３次元的な地質構造や温度構造および物性などを理解することは，火山学的に重要なだけでなく，大陸地殻の発達過程という地学的課題や，将来のエネルギーとしての地熱開発に関する課題，さらには，火山災害の軽減や核廃棄物処理に関する課題としても重要である。

火山体掘削はこれまで国内外で数多くなされてきた。その多くが地熱開発によるものであり，その解析結果は火山学的にも利用されてきた。科学目的が中心の火山体掘削としては，これまでハワイ，カリフォルニア州のロングバレー，雲仙火山，アイスランドなどにおいて，陸上科学掘削計画（ICDP）プロジェクトとして数 km 長の掘削が実施されている。このうちロングバレーとアイスランドの掘削では地熱流体の調査が主なテーマとなっており，ここでも地熱開発との結びつきが大きい。

火山掘削が重要と考える理由は主に以下の 5 点にまとめることができる。

(1) コア試料，検層，その場観測による，地下の物質科学的実体，物性，応力状態等の把握。地上調査や地上探査では得られない情報が取得できる。雲仙普賢岳の火道の構造や，濁川カルデラ・阿蘇カルデラの成因は掘削なくしては解釈できなかった。また，検層結果を用いて探査結果を再評価する上でも有効。

(2) 火山・マグマ発達史を理解。ハワイや富士山で行われた掘削成果で示されたように，火山の発達過程やマグマの進化，さらには，地殻の発達過程やホットスポットの進化の理解を助けることにつながる。

(3) 火山地域における熱的構造の把握および熱水循環系の理解。葛根田の地熱掘削，ロングバレー探査井掘削，雲仙科学掘削，さらにはクラフラ超臨界流体掘削の結果が示すように，掘削なくして熱的構造や熱水系の詳細な理解はあり得ない。

(4) 掘削坑を用いた火山活動の監視。火山現象の発生源に接近した監視・観測は，火山噴火のメカニズムを理解する上だけでなく，噴火を予測し火山災害を軽減する上でも重要である。特に，マグマ貫入場所や通り道および，火道の周囲環境を理解することも，噴火のメカニズムや推移予測の上でも重要である。

(5) 地球規模で甚大な環境変動をもたらす可能性のある超巨大噴火に対する災害予防。カルデラ噴火による影響は国家どころか人類の存続をも脅かす。そのため，超巨大噴火の前兆現象や環境への影響を深部火山体掘削によって理解しておくことが重要である。

キーワード: 陸上科学掘削計画, 火山地下構造, 火山発達史, 火山観測, 火山防災
Keywords: International Continental Scientific Drilling Program, subsurface structure of volcano, development history of volcano, volcanic observation, volcanic disaster prevention

SMP47-02　　会場:203　　時間:5 月 22 日 11:30-11:45

岩手県葛根田地熱地域で脆性－延性境界を貫いた地熱調査井 WD-1a の総括
Summary of the geothermal survey well WD-1a penetrating to the brittle-plastic boundary in the Kakkonda geothermal field

大谷 具幸 [1*], 村岡 洋文 [2]
Tomoyuki Ohtani[1*], Hirofumi Muraoka[2]

[1] 岐阜大学工学部, [2] 弘前大学北日本新エネルギー研究所
[1]Dept. Civil Engineering, Gifu University, [2]North Japan Research Institute for Sustainable Energy, Hirosaki University

脆性－延性境界以深における熱エネルギーの抽出を考えるためには、これまでに岩手県葛根田地熱地域で延性－脆性境界を貫いた地熱調査井である WD-1a の総括をする必要がある。WD-1a は新エネルギー・産業技術総合機構 (NEDO) の深部地熱資源調査プロジェクトの一環として掘削された深部調査井である。孔底深度は 3729m であり、孔底における温度は 500 ℃以上と見積もられている（Ikeuchi et al., 1996; Kato et al., 1996）。この孔井は浅部より第四紀層、第三紀層、先第三紀層が分布しており、深度 2860m 以深には葛根田花崗岩が分布している（Kato et al., 1996）。葛根田花崗岩は黒雲母と角閃石により K-Ar 年代が測定されており、それぞれ 0.068～0.21Ma、0.08～0.34Ma の年代値を示している（蟹沢ほか, 1994）。

脆性－延性境界の観点から見ると、深度約 3km 付近に熱水対流域と熱伝導域の境界（Ikeuchi et al., 1996）、微小地震の震源域の下限（当舎ほか、1995）、フラクチャの有無に関連すると思われる低比抵抗部と高比抵抗部の境界（Kato et al., 1996）が存在しており、WD-1a が脆性?延性変形境界を貫いている可能性が指摘されている（Muraoka, 1997）。深度約 3km 以浅（脆性変形領域）では約 350 ℃以下で数多くのフラクチャが発達して地熱貯留層を形成している（Kato et al., 1996）のに対して、深度約 3km 以深（延性変形領域）では、約 350 ℃以上で岩石にほとんど変形構造が認められない。深度 2936～2937m のコアには花崗岩中に径数 mm の空隙が発達している。これらの 3 次元形態を X 線 CT により測定し（Ohtani et al., 2000）、回転楕円体によるフィッティングを行うと短軸が東西方向を示すことから、広域応力場の影響による短縮の影響が指摘されている（Ohtani et al., 2001）。

熱エネルギーの抽出の観点から見ると、深部に向かって浅部熱水対流系、接触変成帯、深部熱水対流系、延性領域となっており、延性領域では従来型フラッシュ発電に用いるような熱水対流は生じていない（Muraoka et al., 1998）。よって、延性領域から熱エネルギーの抽出を行うためには、EGS（Enhanced Geothermal Systems）等の新たな技術を開発して適用する必要がある。

Ikeuchi et al., 1996, Geotherm. Res. Coun. Trans., 19, 598-505.
蟹沢ほか, 1994, 岩鉱, 89, 390-407.
Kato et al., 1996, Proc. 8th Int. Symp. on the Observation of the Continental Crust Through Drilling, 241-246.
Muraoka, 1997, Geotherm. Res. Coun. Trans., 21, 309-316.
Muraoka et al., 1998, Geothermics, 27, 507-534.
Ohtani et al., 2000, Eng. Geol., 56, 1-9.
Ohtani et al., 2001, Jour. Struct. Geol., 23, 1741-1751.
当舎ほか, 1995, 地質調査所月報, 46, 483-495.

キーワード: 脆性－延性境界, 地熱調査井, WD-1a, 葛根田地熱地域
Keywords: brittle-plastic boundary, geothermal survey well, WD-1a, Kakkonda geothermal field

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SMP47-03 会場:203 時間:5 月 22 日 11:45-12:00

地震メカニズムトモグラフィー法によるバーゼル地熱貯留層での間隙流体圧分布の推定
High fluid pressure and triggered earthquakes in the enhanced geothermal system in Basel, Switzerland

寺川 寿子 [1*], Stephen A. Miller[2], Nicholas Deichmann[3]
Toshiko Terakawa[1*], Stephen A. Miller[2], Nicholas Deichmann[3]

[1] 名古屋大学・大学院環境学研究科・附属地震火山研究センター, [2]Geodynamics/Geophysics, Steinmann-Institute, University of Bonn, [3]Swiss Seismological Service, ETH-Zurich
[1]graduate School of Environmental Studies, Nagoya University, [2]Geodynamics/Geophysics, Steinmann-Institute, University of Bonn, [3]Swiss Seismological Service, ETH-Zurich

We analysed 118 well-constrained focal mechanisms to estimate the pore fluid pressure field of the stimulated region during the fluid injection experiment in Basel, Switzerland. This technique, termed focal mechanism tomography (FMT), uses the orientations of slip planes within the prevailing regional stress field as indicator of the fluid pressure along the plane at the time of slip. The maximum value and temporal change of excess pore fluid pressures are consistent with the known history of the wellhead pressure applied at the borehole. Elevated pore fluid pressures were concentrated within 500 m of the open hole section, which are consistent with the spatio-temporal evolution of the induced microseismicity. Our results demonstrate that FMT is a robust approach, being validated at the meso-scale of the Basel stimulation experiment. We found average earthquake triggering excess pore fluid pressures of about 10MPa above hydrostatic. Over-pressurized fluids induced many small events ($M < 3$) along faults unfavourably-oriented relative to the tectonic stress pattern, while the larger events tended to occur along optimally-oriented faults. This suggests that small-scale hydraulic networks, developed from the high pressure stimulation, interact to load (hydraulically isolated) high strength bridges that produce the larger events. The triggering pore fluid pressures are substantially higher than that predicted from a linear pressure diffusion process from the source boundary, and shows that the system is highly permeable along flow paths that allow fast pressure diffusion to the boundaries of the stimulated region.

キーワード: 間隙流体圧, 応力, 地震のメカニズム解, インバージョン解析, 注水実験
Keywords: pore fluid pressure, stress, focal mechanisms of seismic events, inversion analysis, fluid injection

SMP47-04 会場:203 時間:5 月 22 日 12:00-12:15

地熱フィールドで発生する有感地震の特性
Characteristics of felt earthquakes occurred from geothermal field

椋平 祐輔 [1*], 浅沼 宏 [1], WYBORN, Doone[2], HARING, Markus[3], 安達　正畝 [4]
Yusuke Mukuhira[1*], ASANUMA, Hiroshi[1], WYBORN, Doone[2], HARING, Markus[3], ADACHI, Masaho[4]

[1] 東北大学 大学院環境科学研究科, [2]Geodynamics Ltd., Australia, [3]Geo Explorer Ltd., Switzerland, [4] 奥会津地熱株式会社
[1]Graduate School of Environmental Studies, Tohoku Univ., [2]Geodynamics Ltd., Australia, [3]Geo Explorer Ltd., Switzerland, [4]Okuaizu Geothermal Co., Ltd., Japan

The authors have reviewed three significant cases of the felt earthquakes occurred from geothermal field, Cooper Basin, Australia, Basel, Switzerland, and Yanaizu-Nishiyama, Japan. Recently, the occurrence of felt earthquake from the geothermal reservoir has become critical issue in geothermal development. Microseismic activity is observed in many of hydrothermal reservoirs. It is also common that the microseismic events occurred at hydraulic stimulation of EGS/HDR reservoirs. However, some of the micro earthquakes have unexpectedly so large magnitude and they were felt on the surface. The physics behind such felt earthquakes were not well understood so far.

1. Cooper Basin, Australia

Geodynamics ltd. developed HFR system at Cooper Basin. During the hydraulic stimulation and initial hydraulic test in 2003, several felt earthquakes occurred. The magnitude of the largest seismic events was estimated as *Mw* =3.0 by Geoscience Australia. The felt earthquakes occurred over initial hydraulic test and after shut-in. Hypocenters of the felt earthquake were located widely in the seismic cloud, although, geological structures where the felt earthquakes occurred were not observed. The source mechanism of the felt earthquakes may be common to other smaller events because of identical first motion of the P-wave at monitoring station. Spatio-temporal analysis revealed that the felt earthquakes occurred at the edge of the seismic cloud and then, the seismic cloud extended to the aseismic zone. Many small events were observed within the fault area of the felt earthquake as after shocks. So, it is concluded that the felt earthquake occurred from the asperity which play a role of the hydraulic barrier.

2. Basel, Switzerland

GEL (Geothermal Explorer Ltd.), an operating company of the Basel Project, conducted hydraulic stimulation in 2006 at Basel urban area. First felt earthquake with *Mw* =2.0 occurred at 5th day of the hydraulic stimulation. Then, following felt earthquakes including largest one with *Mw* =2.68 took place just after the shut in from the deep and middle part of the seismic cloud. After one month of the stimulation or later, three large events still occurred and their hypocenters were located in the middle or shallow part of the seismic cloud. Three felt earthquakes from deep part of the seismic cloud were likely occur from common fault plane and showed high similarity in waveforms to the smaller events. However, no apparent extension of the seismic area was observed. In contrast, the similarity in waveform between the felt earthquakes from shallow part of the reservoir was low, suggesting that mechanism was not identical to that of smaller events. In fact, hypocenters of felt earthquakes from shallow part of the reservoir were located outside of the seismic cloud.

3. Yanaizu-Nishiyama, Japan

Geothermal power plant at Yanaizu-Nishiyama, Fukushima, Japan has a 65,000 kW of the capacity and has been operated by Okuaizu Geothermal Co. Ltd. (OAG) since 1995. The hydrothermal reservoir is consisted by caldera-related fracture system and the reservoir is steam-dominant at around 2 km depth. There has been seismic activity for long years in this area and micro earthquakes were surely observed before the operation of the power plant. The hot water is re-injected by gravity feed. Large earthquake were sometimes observed in this area. Largest earthquake with JMA magnitude 4.9 occurred on October, 2009. There was no clear correlation between the operations of production/injection and the occurrence of the felt earthquakes. These felt earthquakes had hypocenters within the cloud of micro earthquakes. FPSs estimated by JMA for four felt earthquakes showed same normal fault plane of NW-SW strike and around 45 deg. of inclination. However, seismic structure where the many of the smaller events occurred had more different orientations. It is interpreted that the felt earthquakes were likely to occur from fracture plane in particular nature.

Keywords: Microseismicity, Felt earthquake, Magnitude, Cooper Basin, Basel, Yanaizu-Nishiyama

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SMP47-05 会場:203 時間:5 月 22 日 12:15-12:30

JBBP 型貯留層からの誘発地震発生モデル
model of induced seismicity from JBBP-type EGS reservoirs

浅沼 宏 [1*], 椋平 祐輔 [1]
Hiroshi Asanuma[1*], Yusuke Mukuhira[1]

[1] 東北大学・大学院環境科学研究科
[1]Graduate School of Environmental Studies, Tohoku University

Induced seismicity is typically observed at EGS (Engineered Geothermal Systems) reservoirs while its creation and circulation/production phases. Many of the hydrothermal reservoirs also have natural or induced seismic activity. The microseismicity has been effectively used as one of the few means which have ability to resolve reservoir extension and structure with practically acceptable resolution. However, some of the seismic events have large magnitude and they brought some degree of damages to houses and infrastructures on the ground surface. In the JBBP, the authors expect that the activity and released energy of the induced seismicity will be reduced, because the reservoir would be isolated in less fractured rock mass in the BDT, and the creation process of the reservoir woulud be different from that in the ductile zones. The authors will disucuss risk of induced seismicity with large magnitude from the JBBP reservoirs showing some possible models of the reservoirs.

キーワード: 能動的地熱開発, 誘発微小地震, ＥＧＳ
Keywords: EGS, Induced seismicity, Stimulation

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SMP47-06 会場:203 時間:5 月 22 日 12:30-12:45

能動的地熱増産システム開発における物理探査の役割
The role of geophysical exploration in detecting and monitoring enhanced geothermal system (EGS)

茂木 透[1*], 内田 利弘[2]
Toru Mogi[1*], Toshihiro Uchida[2]

[1] 北大．理, [2] 産総研
[1]Fac.Sci.,Hokkaido Univ., [2]AIST

The discovery of enhanced geothermal systems (EGS) prescribes the need for novel technology to detect high-temperature areas and monitor fluid contents at depth. To minimize cost and risk, engineers attempt to predict reservoir performance, for both planning and evaluation of geothermal resource development projects. Correct predictions of reservoir performance hinge on how well the reservoir is understood and has been described in the models used for fluid-flow simulation. An important role of the geophysical survey is to provide basic data for a reservoir simulation.

Imaging hot rock and fracture zones and monitoring fracture growth deep in the earth at 3 to 5 km is not a simple task. Regional survey methods such as gravity and airborne magnetic surveys are usually used to delineate regional geologic settings. Some researchers have examined the feasibility of using Curie isotherm depths, estimated from magnetic anomalies, as a proxy for lithospheric thermal structure.

The three-dimensional (3D) magnetotelluric (MT) survey method provides a relatively inexpensive way to obtain accurate images based on electrical conductivity, but the resolution in deeper areas is inherently low. MT is sensitive to conductors, making it a prime method for detecting electrically conductive fluids at depth. The areal extent of a reservoir at depth can be estimated by measuring the MT response before, during, and after fluids are injected. Forward modeling and repeatability estimates will be covered.

The 3D seismic survey method allows for imaging deep fractures with higher resolution. A P-wave reflector is detected at the top of a deep fractured layer, which must lie at the brittle?ductile transition and may be common in areas with magmatic activity. However, performing 3D land seismic surveys in areas with topographic variation is challenging. Even if such a survey could be performed, it would be difficult to image fractures in a crystalline formation because the aperture of the fracture is likely to be thinner than a quarter of the wavelength of the surface seismic wave. Most significantly, it may not be practical to monitor the growth of a fracture using 3D seismic surveys because of high cost.

Reflection imaging with micro-earthquakes generated during stimulation is a possible method for defining major flow paths in deep crystalline formations. The advantage of micro-seismic imaging is its higher frequency spectrum (up to several hundred hertz), meaning that thin fractures can be imaged.

Reservoir characterization, particularly in terms of reservoir architecture, flow paths, and fluid-flow parameters is the key to good reservoir engineering. Geophysical methods will play a central role in future reservoir characterization and in improving EGS monitoring.

キーワード: 物理探査, 地熱資源, 能動的地熱増産システム
Keywords: Geophysical Exploration, Geotheramal Resource, Enhanced Geothermal System