

南海トラフ泥火山の熱・物質輸送から地震発生帯の状態を推定する試み

State of the Nankai Trough seismogenic zone inferred from thermal and hydrological regime of the mud volcanoes

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泥火山は、海溝陸側斜面から前弧海盆にかけて見られる円錐状の構造体である。その頂部に泥が噴出したような形状が見られたり、地下にはdiapir状の構造が水平地層を切っている。深部からの水と、それに伴う堆積物が噴出している。世界の泥火山に関する調査は、地中海、北極海、黒海等中央アジア、バイカル湖、台湾・東シナ海・日本周辺、カスカディア～中米海溝・バルバドスまで多岐にわたる。いずれも、周囲の堆積層よりも密度の小さい泥が、何らかの力で押されることで海底に噴出する。その中で、大陸斜面からの海底地すべりや河川のデルタの外縁などにみられるものは、急激な堆積作用の結果として大量の有機物が非排水・非圧密状態となり、過剰間隙水圧が原動力であろう。一方、南海トラフや中米海溝・台湾などは、プレート沈み込みに伴い海溝陸側の堆積層が水平圧縮されることに加え、間隙水のみならず堆積物の脱水等による新たな自由水の発生により、地層中に過剰圧が生じることで、地中の泥質堆積物が海底に噴出していると考えられる。

南海トラフには、熊野海盆上にいくつか顕著な泥火山が存在する。地震探査記録によれば、diapir状の構造が地下深部から海底まで連続している。泥火山噴出物の起源を知る鍵は、ホウ素、リチウム、メタン中の炭素同位体などの化学的トレーサが有用である。中でもLiは岩石-水系の温度が250-300°Cに達すると流体中のLiの濃度が急激に上昇し、その後冷却しても沈殿せず流体相にとどまることが知られている。このことを利用した熊野泥火山堆積物中の間隙水のLi同位体異常から、その間隙水が経験した最高被熱温度が300°C程度だったと分かった (Nishio et al., 2015)。熊野海盆の平均地温勾配が40mK/m程度であるので、単純計算で300°Cの環境は地下7-8kmに対応するようだ。実際には深度とともに温度勾配は減少するし、そもそも温度分布はプレートの沈み込みやプレート境界面で発生する巨大地震、あるいは地質時間スケールで発達する付加体といった活動により時間とともに変動するであろう。地下温度の時空分布を推定するために、海底での熱流量分布 (BSR深度からの推定や、海底での計測による) を知った上で、プレート沈み込みとそれに伴う堆積物の移動や圧密等を考慮に入れたモデル計算が必要となる。例えばHarris et al. (2011 G3)によると、300°Cに達するのは地下約20kmである。

一方、泥火山の成長に関わる流体排出速度の指標としては、コア試料中の間隙水化学組成 (塩素や硫酸イオン濃度等) や熱流量プローブによる地温勾配の非線形分布、ハイドレート安定領域下限としてのBSR深度の異常、などが重要である。熊野沖の第4泥火山 (KK4) における熱流量測定の結果、泥火山の頂部地形効果により頂部が泥火山の裾野 (~70 mW/m²) に比べてかなり熱流量が低い (~20 mW/m²) ことが分かった。Goto et al. (2007 AGU) は、この異常を地形効果とdiapir内部の流体上昇の相乗効果で説明した。それに必要なだるしー速度は1mm/yearの程度であると推定した。なお黒海や北極海のHakon Mosby泥火山頂部では、10-40K/mという、極めて高い表層地温勾配が観測され、10-30cm/yearというダルシー速度が推定されている。おそらくは熊野泥火山でもある時期にはこのような活発な湧出活動はあり得るであろう。そのような上昇を生じるための原動力として、上述のような地下深部における間隙水圧異常を仮定することができる。もしそれが巨大地震の震源断層上で起きているならば、断層の有効強度が推定できることになり、南海トラフ地震発生帯の切迫度評価に重要な貢献をなすことが期待できる。

なお、最近、熊野海盆の南端、外縁隆起帯付近で、海底泥火山活動および巨大路頭が存在することが、AUV観測により確認された (浅田ほか、本大会)。この部分は地震断層深度が海底下3km程度と浅く、推定温度も100°C程度と低い。陸側の泥火山との関係など、今後さらに調査・考察が必要である。

キーワード：南海トラフ地震発生帯、泥火山、熱流量異常

Keywords: Nankai Trough seismogenic zone, mud volcano, heat flow anomaly

海底泥火山から水圏への海底下微生物群集の拡散

Dispersal of deep-biosphere communities from submarine mud volcanoes to the overlying hydrosphere

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Submarine mud volcanoes along the plate convergent margins represent "natural pipelines" that vertically transport low density, deformable sediments and gaseous compounds from several kilometers below the seafloor to the overlying hydrosphere. For example, methane is supplied through upward fluid advection via the mud volcanism from the deeper hydrocarbon reservoir and microbial communities near the seafloor consume a large fraction of methane through their aerobic and anaerobic oxidation activities on the seafloor. However, the vertical dispersal of microbial components from the subseafloor habitat to the overlying seawater remains unknown.

Since 2012, using the AUV "Urashima" and ROV "Hyper-Dolphin", we performed an intensive seafloor survey of the submarine mud-volcanic structures off Tanegashima Island, showing well-preserved mud-flow channels suggestive of the recent mud-volcanic activities. During the KH-15-2 cruise in 2015, we obtained sediment core and water samples from the summit of MV#1 and MV#14 using a Navigable Sampling System (NSS). The profiles of methane concentrations in the water column showed a small peak (1-2 nM) at about 40 m and 60 m above the top of MV#1 and MV#14, respectively, indicating the existence of methane plume discharged from the submarine mud volcano. To study taxonomic composition of microbial communities in sediment and water-column habitats, we extracted DNA and then sequenced 16S rRNA genes using a next generation sequencer. The sequence analysis demonstrated that microbial community structures are overall very different above and below the seafloor. However, interestingly, we found some common species, such as "*Atribacteria*"-relatives, which are widely distributed in anaerobic subseafloor sedimentary habitats. Moreover, the distribution patterns of those common species correlate with the peaked methane profiles. Our geochemical and microbiological observations suggest that a small fraction of deep-biosphere microbial communities are geomechanically dispersed with methane from submarine mud volcanoes to the overlying hydrosphere.

キーワード：泥火山、微生物群集構造

Keywords: Mud Volcano, Microbial community structure

紀伊半島の中新統田辺層群にみられる浅海性泥火山

Shallow marine mud volcanoes in the Miocene Tanabe group, Kii Peninsula

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The component material and intrusive structures of several mud diapirs in the Miocene Tanabe Group, southwest of the Kii peninsula were examined to reveal the fluid intrusion style and processes. To examine factors controlling the intrusive styles, tank experiments were also performed. Three types of intrusive structures such as cylinder, dome, and sill types were observed in ascending order in the Shirahama Formation overlying the muddy Asso Formation of the Tanabe Group. (1) Cylinder type: The Ichieminami mud diapir, the about 20m in diameter, intruded into bedded sand and siltstones almost vertically. The majority matrix is siltstone, with subordinate sand and quartzose sand in inner part. (2) Dome type: Ichiezaki mud diapir has a dome shape of about 150m in diameter including blocks and sand grains of host sediments by stoping. Many mud dykes radially intruding into hostrocks are clayey in the early stage and sandy in the later stage. (3) Sill type: The mud diapir of the Migusa represents the lens shaped lacolith with at least 200m in diameter, mainly consists of pebbly mudstone involving blocks of surrounding strata. There are small-scale mudstone sills and dykes around the diapir. As a result of tank experiments, it was observed that a series of lenticular intrusive slurry body with dome like upheaval, transforming into the mud chamber expanded involving blocks and particles of the host sediments. As it collapsed, a conduit of upward escaping muddy fluids, sill and dyke structures are formed above the chamber. Based on the correlation between the diapiric structures in the Tanabe Group and intrusive features in the tank, (1) Cylinder type intrusion is indicative of conduit of the fluid to the chamber. Such a vertical path shows a concentrated fluid flow cut through permeable sedimentary strata without any muddy impermeable intercalation. (2) Dome type diapir corresponds to a mud chamber or the upper most part of a cylinder type intrusive body where the stoping process is most predominant. (3) Sill type intrusive body is thought to represent the mud chamber intruded into layered sedimentary sequence with remarkable permeability contrast. These diapirs of the Tanabe Group show a variety of intrusion by a single event that a high-pressured fluid with small amount of mud injected through a narrow conduit to the level where a large mud chamber expands one after another, by which different types of intrusive structures are formed in accordance with permeability contrast and the degree of solidification of the host sediments. Subaqueous debris flow deposits erupted from a mud volcano (Nakaya and Hamada, 2009) more than 100m in thickness have been reported from middle to upper member of the Shirahama Formation. Small scale (less than 20m) fluid intrusion structures were also found in several horizons of the upper member of the Shirahama Formation. At least, some of those structures display characteristic deformation style suggesting the fluid as gas phase. Carbonate nodules and chimneys were found in from the uppermost Asso Formation. The carbon stable isotope ratios of calcite and dolomite in nodules and chimneys ranges from -22 to 7 permil. (PDB), and the oxygen stable isotope ratios ranges from -20 to 0 permil. (PDB). Pyrite nodules less than 10 cm in diameter are formed in the fluid intrusion structures in several horizons of the upper member of the Shirahama Formation. The sulfur stable isotope ratios of the pyrite nodules are ranging from -4.3 to +1.4 permil. (CDT), which are similar of those in carbonate nodules and chimneys. Thermal or deep-seated fluid with CH₄/CO₂/H₂S gases might have been erupted to the shallow water area at the time of regression stage of the Tanabe Group.

キーワード：泥火山、泥ダイアピル

Keywords: mud volcano, mud diapirism

InSARによるアゼルバイジャンの泥火山の活動に伴う地殻変動の検出と地下圧力源の推定
Ground deformation of mud volcanoes in Azerbaidzhan detected by InSAR and estimation of the pressure source

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地表面の変動を検出する方法の一つにInSAR (Interferometric SAR) がある。SAR (合成開口レーダー) は地上に観測点を設置すること無く、面的に地表データを取得することが可能であり、InSARを用いれば、数cmの感度で地表変位の観測をすることができる。本研究では、InSARにより泥火山の変動を検出し、そのデータを元に地下内部の状態を推定することを目的とした。

アゼルバイジャンはカスピ海西岸に位置し、世界でも有数の泥火山を有する中央アジアの国である。JAXAが打ち上げたALOS/PALSARとALOS-2/PALSAR-2(だいち一号, 二号)の2007年から2010年と2014年以降のデータを解析した。結果、十数の泥火山の活動に伴う変動を検出することができた。また、そのほとんどが衛星視線方向に近づく山体の隆起を示す変動であり、この地域一帯の泥火山は活発であることが裏付けられる。その中でも特に大きいAyaz-Akhtarma泥火山 とAkhtarma-Pashali泥火山に特に注目する。Benedetta et al. (2014)では、Cバンド衛星であるENVISAT/ASARの2003~2005年のDescendingデータを用いて、噴火前の変動を捉えることを目的とし、Ayaz-Akhtarma泥火山では二年間で20cm視線方向に近づく結果が得られている。またAkhtarma-Pashali泥火山では二年間で4.5cm視線方向に近づく結果が得られている。しかし、これらに続く研究報告は無く、その後の挙動は分かっていなかった。本研究では、これらの泥火山に対し、Lバンド衛星であるALOS/PALSARのAscendingデータ及びALOS-2/PALSAR-2のAscending, Descendingデータを用いたInSAR解析結果を報告する。その結果、最大で13cm/yrほど衛星視線方向に近づく変位が得られた。また、検出した変動から茂木モデルを用いて地下圧力源の推定を行った。推定の結果、Ayaz-Akhtarma泥火山では圧力源の深さは400m、体積変動量は $1.0 \times 10^5 \text{m}^3$ となった。

キーワード：InSAR、茂木モデル、アゼルバイジャン

Keywords: InSAR, Mogi model, Azerbaidzhan

火星のシレヌム大陸の小丘群に関する地形学的特徴と成因の検討

Distribution and geomorphology of well-preserved pitted mounds in Terra Sirenum, Mars:
Implications for possible mud volcanism

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On early Mars (Noachian to Hesperian Periods with approximate absolute age ranging from 4.1 to 3.1 Gyr [1]), groundwater/hydrothermal systems, estimated from the presence of clay minerals on a global scale [e.g., 2], may have occurred, with diverse evidence including a number of putative mud volcanoes being reported in both the northern lowlands [e.g., 3] and relatively old, southern highlands [e.g., 4, 5]. However, the spatial extent of potential mud volcanism on Mars has yet to be fully understood. Moreover, criteria for distinguishing between mud volcanoes and other analogs (e.g., cinder cones, tuff cones, rootless cones, pingos) has yet to be established.

Here we focus on clusters of mounds within an elongated basin floor (~181 km x ~47 km, centered at 203.4°E, 27°S) in the northern Terra Sirenum region (mapped as early to middle Noachian terrain [1]) of the southern highlands, and analyze their spatial distribution, morphological characteristics, and morphometric parameters using high-resolution images recently acquired by NASA's High Resolution Imaging Science Experiment (HiRISE; 25 or 50 cm/pixel spatial scale [7]) and Context (CTX; ~5 to 6 m/pixel [8]) cameras onboard the Mars Reconnaissance Orbiter (MRO), and high-resolution (2 m/post) digital elevation models (DEMs) created from HiRISE stereo pairs.

Mapping of more than 600 mounds, based on a mosaic of CTX images, reveals the alignment of mounds along regional structures, and spatial concentration of ~150/1000 km². Using HiRISE images, geomorphological characteristics, such as summit pits, meter-size boulders and dune deposits on their flanks, and smoother surface textures relative to the surrounding terrains, can be commonly observed from most of the mounds. Preliminary morphometric analysis of four mounds, calculated from our DEM, show that they have basal widths ranging from ~300 m to 800 m, heights of up to ~40 m, height-to-width ratios of 0.04 to 0.07, and cross-sectional topographic profiles exhibiting convex-upward slopes.

The resultant values are comparable to those of some mud volcanoes on Earth [9], and the slope geometry is highly consistent with the emplacement of yield-strength fluids [10] (e.g., slurries of water and mud or lava flows) rather than deposition of pyroclastic fragments. Though a volcanic origin cannot be ruled out, the combination of their distribution and meter-scale morphology with their morphometry favor a mud volcano origin. If the mud volcano hypothesis is true, their relatively young surfaces suggest that the formation of source reservoirs and conduit openings along regional fissures for erupting mud and water might have occurred during more recent times than Noachian age. This is consistent with other post-Noachian features in the region such as valley networks and collapse depressions which are linked to faults [11]. Additional high-resolution spectral data coverage obtained by the MRO spacecraft in the future will improve mineralogical characterization of the mounds and further discussions of possible diagenetic processes and/or hydrothermal alteration.

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キーワード：泥火山、火星、リモートセンシング

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