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

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Mud volcano is a conical-shape mound with its diameter ranging from several hundred meters to several kilometers. It is characterized by a sub-seafloor seismically-transparent diapir underlying the cone. Intensive surveys of mud volcanoes have been carried out in many areas; Mediterranean accretionary complex, North Sea (Stregga landslide, etc.), Black Sea, Lake Baikal, Taiwan, East China Sea, Nankai Trough, Cascadia, Costa Rica margin, and Barbados. A driving mechanism for the mud diapirism is the buoyance by a negative density of the diaper and the triggering by the tectonic compression due to plate convergence. Depending on the hydrological property of the sediment, pore fluid cannot drain out from the sediment generating overpressures that also promotes the fluid seepage to the seafloor.
In the Kumano forearc basin there are some mud volcanoes. The Li-isotope analysis of pore water in the core samples obtained from the mud volcano revealed that the origin of the fluid is at depth where formation temperature reaches ~300 degC (Nishio et al., 2015EPSL). A simple extrapolation of surface thermal gradient ~40 mK/m gives the depth of 7-8 km for 300 degC. However, the actual depth is deeper because the thermal gradient should decrease with increasing depth. More importantly, the thermal regime is neither one-dimensional nor in steady state. You need 2D or even 3D numerical simulation, taking into consideration of the advective effect of plate subduction, sediment compaction, geological-scale sediment deformation (fold and thrust), frictional heating due to coseismic fault slip, etc. Through matching the surface heat flow data to the model, Harris et al. (2011 G-cubed) inferred the 300degC depth at ~20 km.
An important factor affecting the evolution of mud volcano is the fluid expulsion rate. Since it is important to directly measure the rate, some proxies are used such as nonlinear profile in pore fluid chemistry (Cl, SO4, etc.) and geotherm, or BSR depth anomaly as indicating the base of methane hydrate stability. Goto et al. (2007AGU) reported the heat flow distribution across the Kumano Knoll No. 4 (KK4); the heat flow higher than 70 mW/m2 in the base of the mud volcano, low heat flow (20-30 mW/m2) in the western slope, and heat flow of ~60 mW/m2 in the summit area. Through numerical calculation considering the topographic effect (thermal refraction), they suggest an upward fluid flow rate of ~1mm/year. The driving force of the flow can be the overpressure at ~20km, which is about the depth of plate boundary fault zone causing M8 great earthquakes. The overpressure may be generated along the fault zone due to the dehydration of clay minerals or coseismic dynamic thermal pressurization if combined with the hydrologically undrained condition. As such, we expect that the mud volcano activity can be an important proxy (or window to the seismogenic zone activity) for the assessment of seismic urgency.
Recently, Asada et al. (2016, this meeting) discovered a giant mound and mud flow activity at the seaward edge of the Kumano basin, where a previous 3D seismic survey revealed a distinctive diaper structure. The depth to the mega-splay fault (seismogenic fault) is only 3 km and the inferred temperature is only 100 degC. A further in-depth research should reveal the state of the fault zone, improving our understanding on the Nankai seismogenesis.

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

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.

Keywords: Mud Volcano, Microbial community structure

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 depsits 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 +l.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.

Keywords: mud volcano, mud diapirism

Ground deformation of mud volcanoes in Azerbaidzhan detected by InSAR and estimation of the pressure source

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Interferometric synthetic aperture radar (InSAR) allows us to observe a wide area and two-dimensional information of Earth's surface without the need for ground-based measurement tools with a precision on the order of a few centimeters. The purpose of this study is to detect ground deformation of mud volcanoes in Azerbaijan by InSAR and to estimate the depth and volume change of the pressure source using a Mogi model (Mogi, 1958).
Azerbaidzhan, located on the western edge of the Caspian Sea in Central Asia, is one of the most abundant countries in term of the population of mud volcanoes over the land. We use the SAR images derived from ALOS/PALSAR and ALOS-2/PALSAR-2 launched by JAXA in 2006 and respectively. As a result, we could detect surface deformation mostly uplifting signals at more than 10 mud volcanoes. These observations indicate that the mud volcanoes around the studied areas are active. We noticed two mud especially large volcanoes in Azerbaidzhan, Ayaz-Akhtarma mud volcano and Akhtarma-Pashali mud volcano. Benedetta et al. (2014) also detected the pre-eruptive ground deformation of these mud volcanoes, using ENVISAT/ASAR C-band SAR data for descending pairs that, span from 2003 to 2005. Although the ground displacement at both volcanoes were 20 cm and 4.5 cm for the two years, subsequent movement was not clear. We report the ground displacements both mud volcanoes, using ALOS data for ascending and ALOS-2 data for ascending and descending tracks, respectively. The detected interferograms indicated that the maximum line of sight (LOS) changes were -13cm/yr. Based on the Mogi model, our preliminary estimate of the depth and volume changes are 400 m and 1.0×10^5 m^3, respectively.

Keywords: InSAR, Mogi model, Azerbaidzhan

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 km^2. 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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