Surface deformation of a mud volcano in azerbaidzhan detected by InSAR and its source modeling

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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 a need for ground-based measurement tool with a precision on the order of a few centimeters. This technique has been mainly used to investigate ground deformation associated with earthquakes and volcanic eruptions. However, there have been fewer cases that applied the technique to the deformation related to the activity of mud volcano. The purpose of this study is to detect surface deformation of a mud volcano in Azerbaizhan by L-band InSAR and to estimate its source modeling.
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 used the SAR images derived from two L-band satellites, ALOS/PALSAR and ALOS-2/PALSAR-2, launched by JAXA in 2006 and 2014 respectively. As a result, we could obtain 31 interferograms and detect surface deformation mostly uplifting signals at more than 10 mud volcanoes. These observations indicate that the mud volcanoes around the studied areas are highly active. In particular, we focused on a large and unique, Ayaz-Akhtarma mud volcano. Benedetta et al. (2014) also detected the ground deformation of this mud volcano, using ENVISAT/ASAR C-band SAR data, spanning from 2003 to 2005, only along descending path; InSAR observes the surface from nearly the north to the south in a slant direction along this path. Although the ground displacement at the mud volcano was 20 cm in Line of Sight (LOS) for the two years, subsequent displacements were not clear. However, the results of our study, using ALOS data from ascending path that is opposite look direction from the previous study and ALOS-2 data for ascending and descending paths, indicated more active and larger horizontal displacements. The cumulative LOS displacement is up to nearly 300 cm for five years by ALOS and 100 cm for two years by ALOS-2. Thus we performed the source modeling to explain the displacement, assuming an elastic half-space. The modeling showed this deformation consists of normal slip and tensile opening components.

Keywords: Mud volcano, SAR

Evidence for widespread mud diapirs in norther Kumano Basin, Nankai Trough forearc basin

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Although mud volcanoes (MV) have been studied in Kumano Basin for almost 20 years, the roots of the MVs have received little attention. Morita et al. (2004) published a seismic line across the basin showing mud diapirs sourcing the MVs, but the extent of these diapirs has remained underappreciated. We present JAMSTEC 2D seismic lines across and along the basin axis showing that much of the northern part of the basin is underlain by mud diapirs. The diapirs feed at least 11 MVs in the northern part of the basin, all of which have been surveyed with multibeam bathymetry, high-resolution sonar and sampling. The diapirs range in diameter from 4-6 km and have seismic expression to at least 2-3 km below the seafloor. Older sedimentary layers are tilted upward adjacent to the diapirs and have internal onlap features that indicate several stages of uplift. Bottom simulating reflections (BSRs) that cross-cut the sediment and diapirs are locally disrupted under the MVs, indicating upward migration of fluids through the methane hydrate layers to the surface. Morita et al. (2004) report that mudstone fragments carried to the surface by the MVs range in age from 18.2-13.6 Ma (late Early Miocene –early Middle Miocene), indicating that the mud diapirs, which probably originate within the underlying accretionary prism, passed through the older layers of the forearc basin.
Reference: Morita, S., J. Ashi, K. Aoike, and S. Kuramoto (2004), Evolution of Kumano basin and sources of clastic ejecta and pore fluid in Kumano mud volcanoes, Eastern Nanaki Trough, In: Proceedings of the International Symposium on Methane Hydrates and Fluid Flow in Upper Accretionary Prisms, Engineering Geology Laboratory, Department of Civil & Earth Resources Engineering, Kyoto University, Kyoto, pp. 92–99.

Keywords: mud volcano, Nankai Trough, accretionary prism

Deep-seated mud volcanoes and their impact on seismicity at Nankai (landward of the NanTroSEIZE drilling transect)

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Sediments in subduction zone forearcs experience major and progressive compositional changes as a function of depth and distance to the trench when they are buried through accretion or underthrusting. Fluids primarily exit the system along fault pathways, thereby reducing the stress state along the plate boundary and allowing aseismic slippage. However, little is known about the abundance or role of water within the region of the seismogenic zone itself, and whether such waters leave the system via landward-dipping reverse faults in the frontal or distal portion of the forearc wedge.

In this study, we sampled the sub-seafloor of the Kumano forearc basin of the Nankai accretionary complex, Japan, along the landward extension of the IODP NanTroSEIZE drilling transect. During R/V SONNE cruise SO222 in June 2012 we collected 450 pore fluid samples from 6 sea floor drill rig cores (up to 35 m depth) and 26 gravity cores (up to 8 m depth) at 13 mud volcanoes and additional background sites, all located some 120 km behind the deformation front (and about 50 km landward of the end of the IODP drillings). The data set was complemented by further sampling during R/V SONNE cruise SO251 in october 2016. The material was analysed for major and minor elements and isotopes of H, O, B, Li and Sr. Mud volcano fluids were strongly freshened, with Cl^- as low as 20% of the sea water value, Mg is completely depleted in the most altered samples, and B and Li^+ are enriched to values rarely seen in this environment. B peaks at 16 mM in the most altered samples with B/Cl reaching 200x the seawater value, possibly the highest ever recorded in seafloor pore fluids. Similarly Li/Cl peaks at 50x the seawater value.

The most likely source of pore fluid freshening is mineral dehydration, with complete depletion of Mg and very low Li isotope ratios being typical of hydrothermal systems in igneous rocks. We hence provide the first evidence for water sourced within the subducting ocean crust directly beneath the decollement in the seismogenic zone, which migrates upward through the upper plate wedge and exits through mud volcanoes ca. 15 km above. The presence of water in sufficient quantity to drive mud volcanism in this region coincides with fewer earthquakes in this region of the fault zone.

Keywords: earthquake, mud volcano, Nankai

Estimated activities of submarine mud volcanoes off Tanegashima based on vertical profiles of pore water chemistry

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Submarine mud volcanoes occur along the margins of convergent plates and are formed by the vertical intrusion of low density, deformable sediments from the deep subsurface to the seafloor. Several mud volcanoes have been found at off Tanegashima Island along the northern Ryukyu Trench. Since 2012, we performed an intensive topographic survey of submarine mud-volcanic structures off Tanegashima Island and observed clear mud-flow channels suggestive of the recent mud-volcanic activities at MV#1 (30˚53'N, 131˚46´E; water depth: 1540 m) and MV#14 (30˚11'N, 131˚23'E; water depth: 1700 m) based on the side scan sonar image. During the KH-15-2 cruise in 2015, we obtained two sediment cores from the summit of MV#1 (core length: 361 cm) and MV#14 (core length: 311 cm) using a Navigable Sampling System (NSS). At the MV#1, the chloride (Cl^-) concentration linearly decreased from 550 mM near the sediment surface to 220 mM at 250 cmbsf. Below 248 cm to core bottom, the concentration was constant at ~220 mM. The stable isotopic compositions of pore waters exhibit ^{18}O-enriched and D-depleted isotopic values in proportion to the depletion of the Cl^- concentration, indicating the addition of water from the dehydration of clay minerals that typically occur in the temperature range from 60˚C to 160˚C. In contrast to the MV#1, at the MV#14, the Cl^- concentration only slightly decreased from 556 mM near the sediment surface to 490 mM at core bottom, indicating slow fluid advection. This indicates that the activity of MV#14 is lower than the MV#1. However, the data of stable isotopic compositions of pore water and Cl^- concentrations from MV#1 and MV#14 show same trends, indicating that the end members of fluids derived by clay mineral dehydration are same.
We tried the quantitative evaluation of the difference in the vertical profiles of Cl^- concentrations between MV#1 and MV#14 by using the one-dimensional unsteady advective diffusion model. As the initial state of the Cl^- profile just after the mud eruption, we assumed that the Cl^- concentration in the core bottom at MV#1 represents the original value of the deep sourced fluid, and the Cl^- concentrations were constant from deep to surface immediately after the eruption. We estimated the advection rates of fluids and times after the mud eruption by fitting the numerically simulated depth profiles of Cl^- concentrations to the observed depth profiles. As the result, advection rate and the time after the eruption at MV#1 were calculated to be 10–15 mm/y and 100–200 years, respectively, and those at MV#14 were estimated to be <0.1 mm/y and 8,000–10,000 years, respectively. The preliminary result of the nannofossils observation shows that the Quaternary and the Tertiary species mixed in the sediment sample obtained from MV#14 in which the Quaternary species are dominant in top 50 cm. The nannofossils records suggest that the hemi-pelagic Quaternary sediments have covered on the deep sourced Tertiary sediments which were conveyed to the sea surface from deep sedimentary realm by the mud eruption. The result is consistent with our estimation for the activity of MV#14 based on the Cl^- profile.

Keywords: Submarine mud volcano, Porewater chemistry, nannofossils

Mud volcano distributed around the Kikai-jima Island, northern Ryukyu Arc

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Geological Survey of Japan have carried out research cruises around the Ryukyu Arc since 2008 in order to improve geoinformation of Japan. During three cruises GH14, GK14 and GK15-2 in 2014 and 2015, we found at least eleven mud volcanoes around the Kikai-jima Island of northern Ryukyu Arc using multi-narrow beam survey system. The largest mud volcano with 1-km diameter of the caldera is located at 17 km off SSW of the Kikai-jima Island (water depth: 400 m). Surface deposition collected by a grab sampler from the caldera is composed of grayish silty clay including many subangular pebbles. These pebbles were likely carried from old strata below the sea-floor when the mud volcano erupted in relatively near the past. To investigate erupted ages of the mud volcano may be important for understanding their relation to the fault activity at the forearc region.

Boron isotope ratios in pore fluids from mud volcanoes off Tanegashima

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Mud volcanoes are geological phenomena, where sediments are venting together with gas accumulated in sediments. They play an important role in geochemical cycle as a path from great depths. It is important to investigate chemical and isotopic compositions of pore fluids in surface sediments for understanding geochemical cycle from great depths. Recently, highly accurate topographical survey was carried out over the mud volcanoes off Tanegashima, and a new mud flow was observed on the seafloor of the mud volcanoes off Tanegashima. In this study, we investigated the chemical and isotope compositions of pore fluids from the mud volcanoes off Tanegashima to discuss the origin and migration processes of fluids in the mud volcanoes off Tanegashima.
From August 19 to September 1, 2015, sediments about 350 cm were sampled from the top of two mud volcanoes (MV#1 and MV#14) off Tanegashima during KH-15-2 cruise of R/V Hakuho using a piston corer. From the recovered sediments, pore fluid was immediately extracted on the ship, distributed to a plastic bottle. The sample was added with 3N nitric acid, and was kept in cool and dark place until analysis.
In the pore fluid sample, boron was separated using the micro-sublimation method, and the boron isotope ratio was measured using a multi-collector inductively coupled plasma mass spectrometer. Boron isotopic ratios were expressed as δ^{11}B (‰) as a deviation from the international standard material (NBS SRM 951). Precision was less than 0.9‰. Chloride ion concentration was measured by ion chromatography and oxygen and hydrogen isotope ratios of water were measured at the Kochi Core Center by cavity ring-down spectroscopy.
Concentration of chloride ion decreased below that of seawater with increasing depth in both sites. The δ^{18}O value of water increased with increasing depth and the δD value decreased with increasing depth. In addition, the degree of the change was larger in MV#1 than MV#14. On the other hand, the δ^{11}B value became lower than that of seawater with increasing depth in MV#1, and higher in MV#14.
It suggests that fluids with low-Cl, high-δ^{18}O and low-δD were supplied from the deeper part in both mud volcanoes. In addition, the difference of these change would represent the difference of the flux of deep-sourced fluids, and it suggests that the flux of fluid from the deeper part is larger in MV#1 with larger change than MV#14 with smaller change. Based on the combination of δ^{18}O and δD values of water, the origin of the fluid would be dehydration of clay mineral in both mud volcanoes, and come from a temperature environment of 60 to 160˚C at which the dehydration reaction of clay minerals occurs. Assuming normal geothermal gradient, the temperature environment is estimated to be several kilometers below the ocean floor. Different δ^{11}B values would be due to the degree of secondary processes during ascending through the sediment column, and it could be related to the flux of the deep-sourced fluids.
In this study, the chemical and isotope compositions of pore fluids from two mud volcanoes off Tanegashima were investigated. These mud volcanoes suggested that there was a difference in the flux of fluid from deep layers. In the mud volcanoes with smaller fluid flux, the secondary reactions would occur in the ascending process of the fluid.

Keywords: Boron isotope, pore fluid, mud volcano, off Tanegashima

Hydrocarbon gas accumulation and mud volcanoes in the Nankai subduction margin: Insight from 3D seismic velocity analysis using automatic picking algorithm

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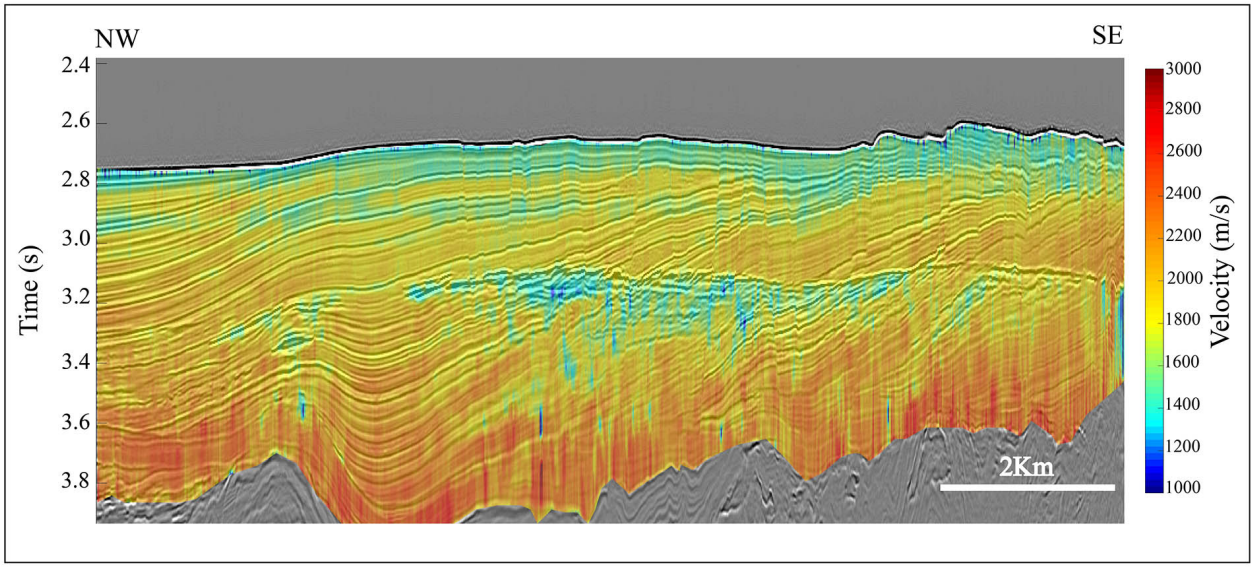
Numerous studies of submarine mud volcano (MV) deposits disclosed subduction-related liquid and gaseous fluids which form and discharge due to the overpressured deep subsurface caused by the overburden of overlying sediments at active continental margins. A variety of MVs have been investigated and known in the Kumano Forearc Basin, which is situated above the Nankai accretionary prism off the Kii peninsula, Japan. When we apply seismic velocity analysis to the 3D seismic data via automatic velocity picking, the results reveal the presence of gas hydrates widespread in this region. The Bottom-Simulating Reflector (BSR) at the base of the gas hydrate stability zone has imaged as a strong acoustic impedance contrast on the seismic profiles. The high accumulation of gas hydrates above BSR and free gas beneath BSR was identified due to high and low velocity anomalies respectively. Based on the results, we suggest that the gas hydrates concentrated due to the free gas influx which migrated upward through the steeply dipping strata and faults or fractures cutting through the basin. The gas (or hydrates) accumulated area is further controlled by the gas charged mud conduits deep rooted in the MVs, and large faults in the accretionary prism. Therefore these factors generated by intensive tectonic movement control the distribution and saturation pattern of gas hydrate and free gas formation, and major sources of these gases may be derived from the deep MVs. When we characterize the features of gas hydrate (i.e., double BSR caused by variation in temperature and pressure within the required duration of thermal equilibrium), we could discuss the history of tectonic and faulting activity in the accretionary prism and specifically the dynamics of the hydrocarbon origin and MVs phenomena.

Keywords: Nankai Trough, Mud volcano, Gas reservoir, Automatic velocity analysis

Seismic velocity overlapping with a stack data IL2528



Preliminary Results of the RV SONNE cruise SO251b in the Kumano Basin (Nankai Trough subduction zone, Japan)

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Mud volcanoes are topographic highs on the ocean seafloor related to expulsion of sediments and fluids from depth. The characterization of the ejecta is helping to constrain the source origin of mud volcanoes and, at the same time, provides important mineralogical, geochemical and rheological information at depths not reachable trough scientific drilling. Off the Kii-peninsula, on the Kumano Basin seafloor, 13 mud volcanoes have been identified from previous scientific investigations in the area (Kuramoto et al., 2001; Morita et al., 2004; Pape et al., 2014). The mud volcanoes' ejecta have been suggested to originate both in the inner accretionary prism and below it, on the plate interface between the Philippine and Eurasian plates (Pape et al., 2014; Toki et al., 2014; Nishio et al., 2015). The Kumano region is known to be subject to large earthquakes, with last occurrences in 1944 (Tonankai, M_w=8.2) and 1946 (Nankai, M_w=8.3) (Ando et al., 1975; Cummins et al., 2002; Linde and Sacks, 2002; Kodaira et al., 2004). Multiple evidences from other regions affected by mud volcanism suggest that mud volcanoes activity is linked with earthquake (Mellors et al., 2007; Kopf et al., 2010; Rudolph and Manga., 2012). Tsunogai et al. (2012) hypothesized such link could also exist for the Kumano Basin mud volcanoes. However, full understanding of this relationship needs to be supported by detailed studies on mud volcanoes to understand their evolution both in time and space, as well as to link them with the seismogenic zone at depth.

Two scientific cruises with the RV SONNE were held on the Kumano Basin in 2012 (SO222) and 2016 (SO251b). The main purposes of the SO251b cruise were (1) to recover the long-term monitoring devices installed in 2012 on 3 mud volcanoes (MV#2, MV#3, MV#4) and (2) to monitor heat flow, pore water geochemistry, bathymetric and subbottom variations on the Kumano Basin seafloor in order to compare the newly acquired data to the SO222 ones.
Four long-term observatories, measuring pressure and temperature in MeBo boreholes, were recovered during multiple dives with the ROV PHOCA from Geomar and are currently under analysis. The long-term data series, together with records from the DONET network, will allow to define the link between mud volcanoes and earthquakes. At the same time, the multibeam echosounder survey (Kongsberg EM122, 12 kHz) was expanded from 2012 to cover most of the Kumano Basin, from 136º10' to 137º30' East. The recently acquired data unraveled a new mud volcano (MV#14, which was also groundtruthed with the recovery of mud breccia) and interesting bathymetric changes in correspondence of some of the most active mud volcanoes (MV#2, MV#13). The differential bathymetry provides constraints on mud flows occurrence between 2012 and 2016. Several loci of possible gas emission (>40) were discovered on the basin seafloor, often situated on top of mud volcanoes or near suspected ones, characterized by strong acoustic signals within the water column. Geochemistry results from sediment cores scattered through the research area showed, according to preliminary analyses conducted onboard, slight freshening with increasing depth, pointing towards a possible deep-seated fluid source. Heat flow measurements with a violin-bow probe through the basin and the active mud volcanoes (identified in 2012) revealed marked differences from the SO222 measurements, supporting ongoing fluid/mud emissions especially on MV#2 and MV#13.

Keywords: Mud Volcano, Kumano Basin, Long-term observation

Why and where submarine mud volcanoes existing? A case study of the Kumano Basin, Naikai Trough subduction zone

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Mud Volcano (MV) is one of topographic feature which derives sediments and fluid from depth to surface of the Earth, which observed over the world (Kopf et al., 2002). They are mainly reported from oilfields, areas of high sedimentation rate, and convergent plate margins. Such loci of MVs suggest that MVism needs stable compressional tectonic setting and/or enough amount of source making MV. MV emits sediment and fluid (gas, water, oil, dissolved salt) (Milkov, 2005). The reason why buried materials intrude upward is that they have buoyancy because of heating (relates to magmatic activity) and difference in density (degassing, dehydration, hydrolysis reaction of mantle wedge, etc.) at the buried depth. Faults maybe help for making upwelling of materials, at some occasions. Because the “MV” is just a topographic feature made by ejecta from depth, background geology of the MVism is too complicate to overview the activity. In order to understand MV itself and desterilize information which MV brings, at least around Japan Island, it is now required that we focus on MV activities around our country and similar geological settings.

MV on and around Japan Island is reported on land (Niigata and Hokkaido area, and hot mud pools) and also at submarine environments (off-Tanegashima and Kumano Basin). There are at least 14 of MVs in the Kumano Basin, the forearc basin at off Kii peninsula (Kuramoto et al., 1998, 2000; Morita et al., 2004; Pape et al., 2015, Asada et al., submitted). Kumano Basin is forearc basin overlying an older accretionary prism along the Nankai Trough, where Philippine Sea Plate subducts under the Eurasia Plate (Moore et al., 2009; Boston et al., 2016). A megasplay fault from the base of the accretionary prism cuts to the seafloor (Moore et al., 2009; Kimura et al., 2011). A fluid sampled from a MV in the Kumano Basin indicate that it comes from deeper than 15 km below seafloor, possibly meaning along plate boundary (Nishio et al., 2015). Results from seismic survey over the Kumano Basin partly show diapiric structure below MVs in the northern Kumano Basin (Morita et al., 2004; Moore et al., in this session). A recently confirmed MV along the Kumano Basin Edge Fault Zone (Asada et al., submitted; Walter et al., in this session) also is considered existing with larger mud diapir nearby, and maybe activated by faults cutting surface of the diapir (Asada et al., submitted). Trying overview the MVism in the Kumano Basin, to pick up characteristic feature of this area, a possible scenario is: (1) ejecta from MV maybe derived from accreted part, (2) environment below a lower sediment layer may decide presence of mud diapir and rough distribution of connecting MV, and (3) tectonic deformation near seafloor controls activity of each MV. Comparative discussion with other submarine MVs are efficient for further understanding of MV in the Kumano Basin. An original depth, history, degree of volcanism, differences between each MV, to know unknown MVs around Japan, and relationship with earthquake remains as unsolved problems.

Keywords: mud volcano, plate convergent margin, mud intrusion/dirpir

