Rock magnetic analyses for understanding of depositional processes of turbidites induced by large earthquakes in Japan Trench

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Ikehara et al., 2016 revealed that the thick turbidite depositions corresponding to 2011 and the other two historical large earthquakes were archived in Japan Trench (JPT) basins. It is then crucially important to determine the distributions of those event deposits in space and time for the JPT paleoseismology. In order to understand the details of their depositions as robust evidences for the large earthquake occurrences, rock magnetic analysis was applied to measure variation of the turbidite intervals. Magnetic granulometry provides the information of sediment depositional processes. Particularly monotone fining upward of magnetic grain size in a few meter scales is found as the most unique feature in the studied sediments. Magnetic grain analysis in detail indicates grain fining occur in various modes. Those variations seem to be linked to respective seismo-events. Additionally anisotropy of magnetic susceptibility (AMS) were measured to detect settling process of particle grains form turbidity flows in the intervals of thick turbidites. Generally dominant lineation of AMS is recognized as not single direction in each event interval while grain size decrease upward monotonously. Some lineations reoriented by paleomagnetic declinations are oblique to the strike of JPT trench. This observation may suggest the complex flow in the confined and elongated basins in JPT. It is considered that the variations of magnetic grain size and fabric data are useful to understand the depositional processes of thick turbidites.

キーワード：タービダイト、日本海溝、岩石磁気学的特徴
Keywords: Turbidite, Japan Trench, Rockmagnetic property

Origin of deep-sea turbidite by stratigraphic variations of terrigenous organic carbon ratio, examples from the off Kii and Boso peninsulas

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Origin of turbidite are important for paleoseismic studies by using deep-sea turbidite, because turbidity currents are caused not only by slope failure during submarine earthquakes, but also by flood and storms. In this study, we try to recognize origin of each turbidite with stratigraphic patters of terrigenous organic carbon (TerOC) ratio by stable organic carbon isotope analyses of deep-sea sediments. Several stratigraphic patterns of TerOC ratio were recognized in turbidite mud deposited by the modern natural disasters, such as the 1596 Keicho-Bungo earthquake, the 1889 Totsukawa Flood, the 1959 Isewan Typhoon, the 2003 flood by Typhoon no.10, the 2004 off-Kii Peninsula earthquakes, and the 2011 Kumano flood by Typhoon no.12 (Omura et al., 2014). Flood-induced turbidite mud have two stratigraphic patterns of TerOC ratio as follows, 1) high and stable TerOC ratio, and 2) low TerOC ratio in lower part and high TerOC ratio in upper part. Slope failure sediments have two stratigraphic patterns of TerOC ratio as follows, 3) low and stable TerOC ratio, and 4) upward decrease of TerOC ratio (Omura et al. 2014). In this study, origin of past deep-sea turbidite are examined by correlation with modern stratigraphic variations of TerOC ratio.
Sediment cores were acquired from the off Kii Peninsula (KT-12-34-PC01, 5.2 m long) at about 2,000 m water depth and the off Boso Peninsula (KS-13-T5-PC02, 9.2 m long) at about 2,500 m water depth by using piston corer. The coring sites of KT-12-34-PC01 and KS-13-T5-PC02 were not directly affected by the submarine canyon. These sediments are composed mainly of olive black clayey silt layers, but includes numerous turbidite layers. Nine intervals of turbidite mud and hemipelagic mud were examined by stable organic carbon analyses. Turbidite mud layers were distinguished from hemipelagic mud by visual examination of soft X-radiographs, on which they show weaker X-ray transmission. Continuous sub-samples were collected at one centimeter intervals from turbidite mud and hemipelagic mud. Total organic carbon contents and stable organic carbon isotope ratio were measured by using an elemental analyzer (Flash EA and Flash 2000) and a mass spectrometer (MAT 253) at the National Museum of Nature and Science, Tokyo. The terrigenous and marine fractions of the organic carbon in the sediment were calculated from the measured stable organic carbon isotope ratio.
In sediment core KT-12-34-PC01, the stable organic carbon isotope ratio was between −19.1‰ and −22.6‰, and the estimated terrigenous fraction was between 0% and 40%. Stratigraphic variations of both flood-induced and slope failure sediments are recognized in TerOC ratio. These results indicate that deep-sea turbidite off the Kii Peninsula were deposited by flood or slope failure. In sediment core KS-13-T5-PC02, the stable organic carbon isotope ratio was between −20.4‰ and −21.7‰ and the estimated terrigenous fraction was between 11% and 28%. Stratigraphic variations of slope failure sediments are recognized in TerOC ratio. These results indicate that deep-sea turbidite off the Boso Peninsula were mainly deposited by slope failure.
The stratigraphic variations of TerOC ratio might be important information for paleoseismic studies by using deep-sea turbidites.

Omura, A., Ikehara, K., Katayama, H., Usami, K., Irino, T., Kuwae, M., Shirai, M. and Ashi, J. (2014)

Stratigraphic variations of terrigenous organic carbon ratios in flood and slope failure sediments of marine area, examples from the modern natural disasters of Japan. 19th International Sedimentological Congress, Geneva, T2S3-P14.

キーワード：タービダイト、陸源有機炭素率、層位変化パターン
Keywords: turbidite, terrigenous organic carbon, stratigraphic variation

堆積構造および化学組成による泥質地震性タービダイトの認定の試み
Identification of muddy seismogenic turbidite from sedimentary structure and chemical composition

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海底堆積物中のタービダイトを用いた古地震研究は世界各地で行われており、様々な成果があげられている。なかでも、近年注目されているのが泥質の地震性タービダイトである。しかし、泥質タービダイトの特徴について報告した研究は多くない。そこで本研究では、堆積構造や化学組成に着目しつつ、試料内における泥質タービダイトの分布を明らかにすることを目的とした。

試料は紀伊半島沖および日向沖の小海盆より採取されたマルチプルコアとピストンコアである。これらの試料に対して、肉眼観察、X線CTスキャン、帯磁率異方性・古地磁気・電気比抵抗測定、XRFコアスキャナーを用いた化学組成分析を行った。

肉眼では無構造の泥質試料においても、奥津ほか（2016, JpGU要旨）で報告したようにCTスキャン画像ではラミナの発達した層とそれを覆う無構造の泥層が明瞭に確認された。さらにXRFコアスキャナーを用いた分析では、CTスキャン画像で認定されたタービダイト層基底部付近でCa値とFe値のピークが確認された。Mn値も全てにおいてではないが同様の傾向が見られた。Ca値とFe値の変動は岩井ほか(2014, 地質学会要旨)の報告と概ね一致する。さらに詳しく見るとFe値のピークのやや上位にCa値のピークが常に存在する。Ca値とFe値の相関は、タービダイト層基底部とそれ以外の層で異なる傾向を示しており、タービダイト層と半遠洋性泥層を判別できる可能性があげられる。Ca値およびFe値のピークは、生物擾乱などの影響で、CTスキャン画像で堆積構造が確認しにくいようなタービダイト層でも見られた。これらのことから、泥質タービダイトの認定においては、X線CT画像に加え、XRFコアスキャナーによる元素分析が有効な手段となると言える。

キーワード：混濁流、イベント性堆積物、地震履歴、南海トラフ
Keywords: turbidity current, event deposit, paleoseismic records, Nankai trough

東日本栃木県に分布する中部更新統宮島層における重力流堆積物の堆積相
Stratigraphic changes and sedimentary facies of lacustrine sediment gravity flow deposits in the Middle Pleistocene Miyajima Formation, Tochigi Prefecture, northeast Japan

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重力流堆積物は深海から湖まで広く認められ，洪水や地震などのイベントとして形成される．海成の場合はその堆積学的な研究が多く行われている一方，これらを堆積させた洪水と崩壊の堆積物の識別やその流れの推定は難しい．湖成重力流堆積物は主に堆積物コアによって研究が行われており，より高い解像度の解析が可能である上，イベントの識別が可能な場合がある．本研究では，露頭における湖成重力流堆積物の堆積相解析による堆積した流れの推定とその層序的変化の取得を行った．

対象とした宮島層は東日本栃木県の那須塩原市に分布する中部更新統の湖成堆積物である．宮島層は年縞堆積物を主体とし，重力流堆積物を多量に挟在する．年縞は*Stephanodiscus niagarae*を主体とする明るい葉理と流入堆積物を主体とする暗い葉理で構成される．対象とした露頭は那須塩原市の中塩原にあり，川沿いに連続的に露出する．本研究では露頭の観察を行うとともに連続写真および柱状試料を採取し，重力流堆積物の層相に基づき区分を行った．また，これらのrecurrence interval，層厚やタイプの層序的変化も検討した．

連続写真を用いた検討では，1177年分の年縞と634層の重力流堆積物が得られた．年縞の平均層厚は1.2 mmであり，重力流堆積物の平均層厚は9.3 mmである．重力流堆積物は，310層の級化するタイプ，315層の塊状タイプ，9層の逆級化するタイプに区分できる．最上部の数層を除いて，重力流堆積物は主にシルト質なマトリックスを持つ．また，それぞれのタイプは，下位を侵食するか否か，リップアップクラストを含むか否か，砂質か否かで細分した．

本層の重力流堆積物は流入性のシルトや砂を含むため，ほとんどは洪水性であると考えられる．また，スランプ構造を示すものや珪藻のブロックを多量に含む，洪水によって引き起こされた斜面崩壊堆積物と考えられるものも含む．基本的に，基底を侵食するタイプの重力流は湖底まで潜り込んだハイパーピクナル流，基底を侵食しないタイプの重力流は湖面もしくは温度躍層で潜り込まずに一度拡散して沈降したホモピクナル流もしくはハイポピクナル流であると推定される．重力流堆積物に認められる級化は通常のハイパーピクナイトやホモピクナルあるいはハイポピクナル流による堆積の特徴である一方，逆級化はハイパーピクナル流の加速の段階の堆積が侵食されなかった場合であると推定される．リップアップクラストを含むものは斜面や湖底で基底を巻き込んだと示唆される．塊状のタイプのうち，細粒なものはフロックとして堆積した可能性が示唆される．

本層の年縞と重力流堆積物は下部720年と上部450年で異なる傾向を示す．年縞は上部では，1年に2セットの年縞を形成した”double laminae”と重力流堆積物は侵食しないタイプが多い．一方，下部では，double laminaeは少なく，重力流堆積物は侵食するタイプが多い．これらは下部と上部で湖水の成層状態が異なることを示唆する．double laminaeは湖水が1年間に夏季と“寒い”冬季の2回成層し，珪藻の繁茂のピークが2度起こったことで形成される．そのため，上部450年では，重力流は湖水が成層したもしくはその成層状態が残っていた時期に湖底まで潜り込むことが難しく，そのため侵食しないタイプが増加したと示唆される．

キーワード：重力流堆積物、ハイパーピクナル流、年縞、湖成層、宮島層、塩原層群
Keywords: sediment gravity flow deposit, hyperpycnal flow, varve, lacustrine sediment, Miyajima Formation, Shiobara Group

Sedimentary structures within sedimentary gravity flow deposits formed under upper flow regime conditions and their association with sedimentary topography

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Sedimentary structures formed under upper flow regime conditions (Fr > 1), such as massive structureless units, spaced planar laminations (SPLs), and occasionally hummocky cross-stratification mimics (HCS mimics), are observed within the lower portions of sediment gravity flow deposits. These structures are overlain by planar laminations and ripple cross-laminations formed under lower flow regime conditions. The resulting successions of structures, formed under both flow regime conditions, constitute Bouma and Lowe sequences. The lower unit of sediment gravity flow deposits is typically dominated by massive structureless units, and SPLs and HCS mimics are not frequently observed. Additionally, it has been suggested that the structures in the lower unit often change with respect to one another along the lateral or paleocurrent directions, as well as vertical directions. However, the depositional processes responsible for the formation of these sedimentary structures are unclear and detailed descriptions of the transitions are rare, particularly for the lateral and paleocurrent directions. Well-exposed, laterally continuous sediment gravity flow deposits in outcrop can provide insights into the depositional processes that formed the structures in the lower unit. In this study, we carried out detailed mapping of these sedimentary structures and the basal topographies within sediment gravity flow deposits, and determined their transitional patterns.

We investigated the turbidite succession of the Neogene Aoshima Formation, Miyazaki Group, which is well-exposed in the paleocurrent direction along the Nichinan Coast of Miyazaki and Nichinan cities. The studied outcrop, located at Shirahama, shows sediment waves with wavelengths of 300–400 m. The sedimentary structures in the sediment gravity flow deposits, which can be traced for approximately 700 m, were mapped using a series of sequential photographs taken at the outcrop. The sediment gravity flow deposits were selected for mapping based on their basal topographies, which are characterized by moderately undulating, slightly undulating, and relatively flat intervals.

The sediment gravity flow deposit facies of the Aoshima Formation have been subdivided into graded, massive, and inverse graded bed types. These bed types show SPLs and HCS mimics in the basal interval. Paleocurrent directional mapping of the sedimentary structures showed that SPLs are dominant in the relatively flat beds; whereas, in the undulating intervals, HCS mimics and SPLs are observed on the upstream and downstream flanks, respectively. When sediment waves are formed as cyclic steps, it is suggested that massive structureless units can be deposited on the upstream flank due to a hydraulic jump; whereas, SPLs are dominant on the downstream flank due to high shear stress flow. In the Aoshima Formation, HCS mimics on the upstream flanks may have been deposited by relatively erosive flows associated with breaking waves, not only hydraulic jumps, because the basal undulations in the study interval are not large enough to have developed clear sediment wave topographies. In contrast, in the intervals characterized by relatively flat topography, it is suggested that laterally continuous SPLs, which extend for tens of meters, may have been deposited under conditions without the effects of basal topography.

キーワード：重力流堆積物、高流砂階、セディメントウェーブ、堆積構造、青島層
Keywords: sedimentary gravity flow deposits, upper flow regime condition, sediment wave, sedimentary structure, Aoshima Formation

サージ継続時間が混濁流の流速分布及びサイクリックステップの形態に与える影響：水路実験におけるサージ的混濁流のPIV測定

Effect of surge-duration on the velocity distribution of turbidity current and resultant cyclic step morphology: PIV measurements of the surge-type turbidity currents in flume experiments

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Cyclic steps are often found in channels on the prodelta surfaces or submarine canyons, which is attributed to turbidity currents. Field observations of turbidity currents and seabed topography on the Squamish delta in British Columbia, Canada revealed that cyclic steps formed by the surge-type turbidity currents. The high-density portion of the flow, which affects the sea floor morphology, lasted only 30-60 seconds (e.g., Hughes Clarke, 2016). We are doing flume experiments aiming to investigate the relationship between the condition of surges and resultant morphology.

Experiments had been performed at Osaka Institute of Technology. A flume, which is 7.0 m long, 0.3 m deep and 2 cm wide, was suspended in a larger tank, which is 7.6 m long, 1.2 m deep and 0.3 m wide, filled with water. The inner flume tilted at 7 degrees. As a source of turbidity currents, mixture of salt water (1.17 g/cm^3) and plastic particles (1.3 g/cm^3, 0.1-0.18 mm in diameter) was prepared. The concentration of the sediments was 6.1 weight % (5.5 volume %) in the head tank. This mixture of salt water and plastic particles poured into the upstream end of the inner flume from head tank for 3-, 5-, and 7-seconds and continuous flow. For 3-, 5-, and 7-seconds-surges, 130 or 140 surges were made respectively. Discharge for unit time ranges 102 to 290 mL.

As a result, surge-type turbidity currents, regardless the surge duration, formed cyclic steps, but the continuous currents did not form cyclic steps. Moreover, the locations where the steps moved upstream vigorously differ from each other, the shorter the duration, the closer to the upstream end.

The velocity distribution of the profile of the turbidity currents were measured using PIV. Comparing the median velocity of 3s-, 5s-, 7s-surges and continuous turbidity currents, it is revealed that the longer the surge duration, the faster the median velocity for the same unit discharge.

キーワード：サージ的混濁流、サイクリックステップ、水路実験、サージ継続時間、PIV測定
Keywords: Surge turbidity current, cyclic step, flume experiment, surge duration, PIV measurement

Three types of submarine canyons offshore southwest Taiwan

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The sea floor off SW Taiwan is represented by an active margin. Morphologically, the margin is occupied by the narrow Kaoping shelf (<10 km) and the broad Kaoping slope which extends to a depth of about 3000m. Several submarine canyons are located on the active margin off SW Taiwan. Looking from NW to SE, these canyons are the Penghu, Shoushan, Kaohsiung, Kaoping, Fangliao, and Hongtsai canyons. Although these canyons are under the same regional controls (i.e., tectonics, sea level change), they have evolved with time and resulted in distinct morphologies.

Canyons off southwestern Taiwan are classified into three different types: 1. river-connected; 2. shelf-indented; 3. blind (confined to the slope). Type 1 canyon, the Kaoping Canyon, is directly connected to the Kaoping River, and is supplied with much sediment. The canyon head segment thus has relatively high tendency to generate hyperpycnal flows during flood seasons. The Penghu, Shoushan, Kaohsiung, and Fangliao canyon belong to type 2. The Fangliao Canyon is intensely incised into the shelf. The other three canyons are characterized by relatively weak headward erosion into the shelf. The Hongtsai Canyon is a type 3 canyon and is mainly resulted from activity of mud diapir and thrust faulting.

Keywords: submarine canyon, Taiwan

Development Processes of Turbidity Currents Toward the Equilibrium State: Examination by Numerical Simulation

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In this study, development processes of turbidity currents toward the equilibrium state was investigated by the numerical simulation using the renormalized group k-epsilon turbulence model. Turbidity currents are particle-laden currents driven by gravity, which occur in deep seas and lakes. It has been indicated that turbidity currents run out over tens to hundreds of kilometers and deposit vast amounts of sediments on submarine fans of deep sea floors. Existing layer-averaged numerical models of turbidity currents, however, cannot reproduce such long-traveled turbidity currents because the flows entrain the ambient water and get diluted as they run down. Recently, Luchi et al. (2015) developed the vertically resolved k-epsilon model of turbidity currents in the steady condition, and implied that turbidity currents become bipartite at the horizon showing the maximum flow velocity. Their model indicated that the upper parts of turbidity currents get rarified as they run down, whereas the lower parts which carry most of the suspended sediment have the equilibrium state, which can be sustained over long distances without any dilution and deceleration. Although this model might explain the reason why turbidity currents can run out for long distances, their model assumed the steady state, so that it was not explained whether the flows can reach the equilibrium state within realistic spatio-temporal scale in the actual sedimentary environments.

Therefore, this study focuses on the processes of both temporal and spatial developments of turbidity currents to become the equilibrium state. This study conducted the two-dimensional numerical simulations using computational fluid dynamics software FLOW-3D in order to obtain spatio-temporal change of flow properties of turbidity currents in both vertical and flow-parallel directions. The simulation was conducted under the condition at which the turbidity current continued flowing from the upstream end of the computational domain at constant rates of velocity and sediment concentration for a given time. The computational domain was 200 m long and 30 m deep, and the computational grid size was 5 cm for both vertical and horizontal directions. The flow velocity and height at the upstream boundary were respectively fixed to the values 1 m/s and 0.5 m, and the experimental duration was set to 1800 seconds. As a result of simulation, we obtained the following findings: (1) the turbidity current reached the steady state about several minutes after the beginning of simulation, (2) the height of the horizon showing the maximum velocity was constant in the region about 4 m from the inlet to the downstream end, (3) the maximum velocity converged to the constant value at about 150 m from the inlet, and (4) the flow height defined by the inflection point of the flow velocity profile continuously increased downstream. These results suggest that the lower part of the turbidity current reached the equilibrium state within about 150 meters at the given experimental condition, whereas the upper part of the flow remained non-uniform because of entrainment of the ambient water. Although further numerical simulations at various experimental conditions are required to conclude, we tentatively infer that the lower part of turbidity currents at natural scale can easily reach the equilibrium state and the upper part continues being rarified. In the future, this study will lead to the development of a new layer-averaged model of two-layered turbidity currents which can solve the large-scale morphodynamic problems.

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キーワード：turbidity current、numerical simulation、development processes
Keywords: turbidity current, numerical simulation, development processes

Inverse analysis to reconstruct hydraulic conditions of non-steady turbidity currents considering multiple grain-size classes

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Turbidity currents emplace turbidite sandstones that are characterized by graded bedding. In spite of their significance in the paleoenvironmental researches and the resource geology, the flow properties of turbidity currents in deep-sea environments remain unclear because in-situ measurements have been disturbed by their highly destructive nature and infrequent occurrences. Therefore, in order to understand the behavior of actual turbidity currents, this study aims to develop a new method of the inverse analysis to reconstruct the paleo-hydraulic conditions of turbidity currents from ancient turbidites. There have been a few studies of inverse modeling of turbidity currents; however, several problems in their studies have been pointed out. For instance, the previous study employed the oversimplified forward model that assumes temporally steady flows, which cannot produce graded bedding. Normal grading and other successive transition of sedimentary structures (i.e. the Bouma sequence) is typical features of ancient turbidites, so that their steady-flow assumption is not suitable for analysis of natural turbidity currents. In contrast, the author inverse model employed two-dimensional Navier-Stokes equations for the forward model, but the calculation cost of their method is too high to apply it to the field-scale data. To this end, this study proposes a new forward model of non-steady turbidity currents with consideration of mixed grain-size sediment, which can describe the behavior of a turbidity current that deposits a typical turbidite showing graded bedding. Our model employs the one-dimensional shallow water equation, which is applicable to the field-scale problems. The “lock-exchange” type condition is assumed as the initial setting in this model. For inverse analysis, the objective function is defined as sum of squares of deviations between the results of the observation and the numerical calculation. In our inverse calculation, the initial hydraulic conditions that minimize the objective function are explored by the genetic algorithm. Tests of our inversion method using the artificial data provided reasonable results, suggesting adequacy of the optimization methodology. We then applied our method to a turbidite in the Kiyosumi Formation, Boso Peninsula, Japan. The Kiyosumi Formation is composed of sand-dominated alternations of turbidite sandstone and hemipelagic mudstone, which are considered to be deposits of the submarine fan lobe. In this study, the individual turbidite bed intercalated between the two key-tuff layers was correlated over 20 km, and thickness and grain-size distribution of the bed were measured at the seven sampling localities. As the result of the inverse analysis, the hydraulic conditions of the turbidity current that had emplaced the turbidite bed was estimated. When the flow reached at the downstream end of the study area, the flow thickness, velocity, and total sediment concentration were reconstructed to be 334.55 m, 0.98 m/s, and 0.0058% respectively at the downstream end of the sampling area. Although the verification of this result will be discussed as a future issue, these reconstructed values are in agreement with the hydraulic conditions of turbidity currents monitored by the previous studies.

キーワード：逆解析、混濁流、タービダイト、清澄層
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