COARSE CLAST DOMINANT SUBMARINE DEBRITE, THE MIO-PLIOCENE FUJIKAWA GROUP, CENTRAL JAPAN

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Abstract. Good examples of deep-water debrite, transported on a steep slope, are preserved in the Mio-Pliocene Minobu and Akebono Formations in the Fujikawa Group. The debrite is divided into two facies, coarse clast dominant conglomerate (CDC) and slurry sandstone (SLS). The CDC, about several to 20 m thick, is composed mainly of pebbles and/or boulders of mafic volcanics together with a small amount of mud matrix. The matrix is poorly developed, less than that judged necessary for a debris flow with Bingham behavior. The CDC commonly shows inverse-to-massive or massive-to-normal gradings. The CDC occurs as a lenticular sedimentary body with a primary relief above the depositional surface, and was interpreted to be the product of a coarse-grain dominant debris flow of dilatant behavior. The CDC often grades vertically to SLS which consists of fine to very coarse sand and a muddy matrix together with mud chips. It is poorly-sorted and usually structureless. The SLS ranges from 10 cm to 3 m in thickness. The beds also show a lenticular shape with primary relief above the depositional surface, and the bed base is flat and smooth with only minor evidence of erosion. The SLS was interpreted to be the result of the tail or intertsurge part of the debris flow that emplaced the CDC. Based on the debris flow mechanism proposed by Takahashi (1977), the coarse-grain dominant debris flow that emplaced the CDC and SLS would require a steep slope, more than 13°, for its flow initiation. This estimation is likely to be supported from the field evidence that a fault escarpment was present at the time.

1. Introduction

Gravity-induced sediment failure is an interesting geomorphologic phenomenon caused by floor instability. Sediment failure, involving both superficial and subsurface (to depths of a few hundred meters) sliding and collapse in deep-water environments has been reported from most modern settings. These include not only passive margins such as the Grand Banks Slide of 1929 (Heezen and Drake, 1964) and the Mississippi Submarine Fan (Coleman et al., 1983), but also active margins such as the Kashima No. 1 Seamount in the Japan Trench (Kobayashi et al., 1987). However, ancient deep-water sediment failure has been poorly understood.

As the study of flow behavior and its product, modern subaerial sediment-water mixing, has increased, more quantitative physical properties and features have come to be known (e.g., Takahashi, 1977; Suwa and Okuda, 1982; Pierson, 1980; Pierson and Costa, 1987). If such modern subaerial studies are effectively utilized for the interpretation of ancient examples, it is inferred that more precise reconstructions of ancient sediment
failure can be achieved. In this paper, I aim to document the sedimentary facies of the ancient failure deposits in the Fujikawa Group, probably transported on a steep slope, and to discuss the initial slope condition based on the flow mechanism proposed by Takahashi (1977) and on the geologic evidence.

2. Regional Setting

In central Honshu around the Izu Peninsula, there is a geomorphologic bending structure including the pre-Miocene geologic belt of the Southwest Japan Arc, Tertiary and Quaternary systems, chiefly of deep-water sediments, (the Izu Collision Zone) and modern trough axes (Fig. 1). With the application of plate tectonics to this region, it has been interpreted that the bending structure was constructed by the collision between the Honshu (mainland of Japan) and Izu-Ogasawara Arcs (e.g. Matsuda, 1978; Niitsuma, 1984). In the Izu Collision Zone, submarine volcanics and volcanioclastics of Early to Middle Miocene in age, and thick trough-fill detritus ranging from the middle Miocene to Pleistocene in age, are exposed repeatedly from north to south. It is believed that this zone has recorded the

Fig. 2. Geologic sketch map of the Fujikawa Group around the Minobu Area, showing the distributions of debrites. 1: fault, 2: anticline axis, 3: syncline axis.
collision event between the Honshu and Izu-Ogasawara Arcs since the Miocene (AMANO, 1986; SOH, 1986; TAKAHASHI, 1986).

The Fujikawa Group comprises the western portion of the Izu Collision Zone, near the western flank of Mt. Fuji (MATSUDA, 1961). The Fujikawa Group is composed of volcanioclastic and clastic materials, and reaches approximately 6 km in thickness; the depositional age of the group ranges from middle Miocene to Pliocene (ODA et al., 1987). The study area occupies the northern part of the distribution of the group (Fig. 2). In the study area, the Fujikawa Group is interpreted to be composed of two different sedimentary domains: the trough domain, as a remnant plate boundary between Honshu and the Izu-Bonin Ridge (SOH, 1986; Taira et al., in press), and the volcanic seamount domain (Fig. 2). The two domains are bounded by the Minobu Thrust of MATSUDA (1958); which stratigraphic separation is likely to be more than 6 km. The Minobu Fault is interpreted as a growth fault (e.g. KIMURA, 1969 MS).

The trough domain is composed mainly of coarse- and fine-grained clastic turbidites. It can be divided into three formations, the Shimobe, Minobu and Akebono Formations in ascending order (AKIYAMA, 1957; MATSUDA, 1958; 1961). Sedimentological study shows that the trough basin has an axial channel extending NNW-SSE and deepening toward the south. The trough basin is interpreted to be similar in shape and dimension to the modern Suruga Trough (SOH, 1986). The water depth of the trough basin was below 1000 m, judging from the study of benthic foraminifera (KANO et al., 1985). The upper horizon of the Akebono Formation, however, is composed mainly of shallow fan-delta sequences.

Two formations are defined in the latter domain: the Kuonji Mudstone, consisting of hemipelagic mudstone together with thin-bedded tuff layers, and the Takatoriya Pyroclastics, of mafic volcanics and volcanioclastics with a small amount of mudstone, in ascending order (Fig. 3). The Kuonji Mudstone reaches about 700 m, and the Takatoriya

Fig. 3. Outview of the coarse-grain dominant debrite from west Taira, showing chaotic texture with angular volcanic blocks in a clayey matrix. The maximum clast size is 3 m in diameter (fragment of andesite lava). Scale bar 1 m long.
Pyroclastics up to 3000 m in thickness. Two or three depocenters of the Takatori-yama Pyroclastics can be defined from north to south (Matsuda, 1961), suggesting the presence of volcanic seamounts.

The debrites (debris flow deposits) are contained in the trough domain (Fig. 2), and are particularly well-exposed in the boundary horizon between the Minobu and Akebono formations along the north-south trending Fuji River.

3. Description of Debrite

The debrites in the study area are commonly poorly sorted, containing volcanic clasts of various sizes within a less-developed mud matrix (Figs. 3 and 4). The clasts are composed chiefly of mafic volcanics, andesite and/or basalt, showing holocrystalline texture and subangular to angular in shape. The petrologic features are quite similar to those of the

![Photomicrograph of the debrite. 1: matrix of debrite (CDC), showing the angular particles of plagioclase and pyroxene within the clay matrix. The andesite, left, is a fragment of a large clast, up to 40 cm in diameter. Scale bar 20 mm. 2: matrix of debrite (SLS) with a fragment of calcareous algae and carbonaceous fragment, showing supplement from shallow marine environments. Scale bar 20 mm.](image-url)
Takatori-yama Pyroclastics (SHIMAZU et al., 1984). Calcite and/or quartz veins are
developed in some clasts, but these never continue to the matrix. The debrites have small
amounts of shale pebbles, sub-round to round grades and derived shallow marine fauna;
*Pecten* sp., calcareous algae and subaerial carbonaceous fragments (Fig. 4).

Fig. 5. Topographic map and geologic columnar sections around Ichirizuka; A: topographic map plotting the
location of outcrops showing the thinning-out of the debrite within thin-bedded turbidites. Dotted layer is a
small-scale pebble mudstone bed. B: geologic columnar sections obtained from the square on A, showing thinning-
out pattern of the debrite. A dacitic tuff bed can be a key bed through the area. CDC: coarse-grain dominant
conglomerate; SLS: slurry sandstone.
The debrite bed shows lenticular geometry in profile normal to the probable transport direction. Some geologic sections around Ichirizuka offer a good example (Fig. 5). In the section logged in the northern Ichirizuka, thin-bedded turbidites and debrite, in ascending order, are exposed, and the relationship between the debrite and the underlying strata is smooth and conformable. In contrast, thin-bedded turbidites widely occupy the same stratigraphic horizon of the debrite without a large break in the southern Ichirizuka section, about 400 m in lateral distance from the north section. Even at the outcrop scale the fact that the debrite bed thins out abruptly can be directly observed. In Fig. 6, the base of the debrite also appears flat and smooth, so that erosion cannot account for the rapid thickness changes of the debrite bed.

Otuka (1955), Matsuda (1958; 1961) and Shimazu et al. (1984) defined the debrites as a laterally continuous layer of pyroclastics and named them the Karasumoriyama pyroclastics. However, several facts mentioned above suggest that the deposits are not 'pyroclastics'.

Based on the texture, structure and clast or grain size, the debrite can be divided into two sedimentary facies, coarse clast dominant conglomerate (CDC) and slurry sandstone (SLS).

![Fig. 6. Sketch of the debrite at a cliff, west Taira, showing the bed morphology of debrite (CDC and SLS). (No vertical exaggeration). Maximum clast size contained is up to 8 m. TBT: thin-bedded turbidites, CDC: coarse-grain dominant conglomerate, SLS: slurry sandstone.]

3.1 Coarse clast dominant conglomerate (CDC)

CDC is a clast-supported conglomerate (Fig. 9), and the commonest debrite facies in the study area. It shows inverse-to-massive or massive-to-normal type conglomerate in the sense of Davis and Walker (1974). The matrix is composed of poorly-sorted mudstone (Fig. 4); the total amount of matrix ranges from a few to 30%, but is commonly less than 10% (e.g. Fig. 9). The clasts consist chiefly of cobble to boulder grades, and the largest one exceeds 10 m in its longest axis. The clasts are usually dispersed in the bed, and no clumps of clasts are recognized. Deformed slump blocks of volcanic mudstone, ranging from 30 cm to 4 m in diameter, are also included as clasts, but are not common. The CDC ranges from several meters to 20 m in thickness, but thins out laterally without evidence of major erosion. That the CDC had primary relief above the depositional surface is indicated by the progressive onlap of the overlying thin-bedded lithology.

Wet-sediment deformations such as injections are often observed in the thin-bedded turbidite beneath the CDC (Fig. 7), but never observed in any overlying thin-bedded
Fig. 7. Wet-sediment deformation caused by overburden due to an abrupt CDC deposition. Hammer is 28 cm long. 1: Injection structure from underlying thin-bedded turbidites into CDC. The sandstone layer, up to 10 cm thick, is folded and cut by a poorly-sorted mudstone injection. 2: Thick sandstone bed in the turbidite beneath CDC was injected by mudstone and deformed. 3: lateral change of 2. The sandstone bed was cut and rotated, and lost its original position resulting from wet-deformation.

turbidites. The injections into the CDC commonly occur at the bed base of the marginal part, and were not intruded vertically, but rather slightly bent toward the margin of the body.

Dropstone-like pebbles and/or cobbles are found in the neighboring strata (Fig. 8). They are also mafic volcanics, ranging from 10 cm to 2 m in diameter, and are quite similar
in their composition and clast angularity to those of the CDC.

3.2 Slurry sandstone (SLS)

SLS consists of fine- to very coarse-grained sand dispersed in an abundant muddy matrix with abundant mud chips (Fig. 9). The mud chips are usually irregular in size and shape, and the boundaries between chips and matrix are poorly defined. SLS also contains mafic volcanic and shale pebbles, but the clast sizes are smaller, from 1 cm to 5 cm in diameter. The SLS is thickly bedded, ranging from 10 cm to 3 m, and is usually massive and structureless except for a very few crude parallel laminations. The bases and tops of the SLS are smooth, flat and well defined. The SLS is commonly distributed covering the CDC (Fig. 6).

4. Facies Interpretation

4.1 Background of debris flow

A debris flow exhibits strength and buoyancy that permit it to carry clasts denser than the bulk density of the flow itself. The strength can be divided into two components, frictional and cohesive strength. The frictional strength is generally produced by a
framework of grain-to-grain contact in static or very slow flow movements. Within zones of little or no deformation by internal shearing, about one-third of the clast weight would be supported by the static frictional strength (PIERSON, 1981). However, as progressively more shears occur in a rapidly moving slurry, the dynamic elements of kinetic friction and dispersive pressure are added and will at some point become dominant over the static friction.

The cohesive strength of a clay-water slurry, proportional to the clay concentration, has been suggested as an important support mechanism of gravel-grade clasts by a number of investigators (e.g. JOHNSON, 1970; HAMPTON, 1972; RODINE and JOHNSON, 1976), but it has been confirmed that the frictional strength resulting from clast-to-clast interaction far exceeds cohesive strength as a clast-support mechanism in debris flows (TAKAHASHI, 1981; PIERSON, 1981).

Buoyancy is interpreted to be a major support mechanism that has the ability to support about two-thirds of the weight of large particles (PIERSON, 1981). Buoyancy is considered to be produced not only by the density difference between slurry and particle, but also by pore pressure in the fluid. As grain concentration increases, excess pore pressure, and buoyancy increases, however, more and more grains come into contact with each other, and less of the load is supported by the fluid (PIERSON, 1981). Too many
non-cohesive grains would cause an increase of internal friction that would overcome the increased buoyancy, and then the flow would be inhibited.

Examples of modern subaerial debris flows show that they can be divided into two types, low-competence muddy flows and high-competence coarse-grain dominant flows. The former typically shows a laminar viscous flow, and a rigid plug is recognized. Previously published papers concerning the flow behavior and mechanisms of the muddy flows are too numerous to be summarized here. Representative studies are Johnson (1970), Hampton (1972, 1975, 1979) and Rodine and Johnson (1976).

In contrast, high-competence coarse-grain dominant debris flows have been little reported (e.g. Takahashi, 1977, 1981; Pierson, 1980; Suwa and Okuda, 1982). These differ in some flow characteristics from the low-competence muddy flows. A longitudinal profile of a subaerial high-competence coarse-grain dominant debris flow (Suwa and Okuda, 1985) shows that the flow can be subdivided into two parts, a main body and a tail or inter surge flow. Several photographs taken from the coarse-grain dominant debris flow in the Yakedake indicate that the snout, the front of the main body, is composed of highly-concentrated coarse-grain clasts without muddy water-clay mixtures (e.g. Suwa and Okuda, 1973; 1985). Experimental studies (Takahashi, 1977; Suwa, in press) suggest that active clast-to-clast interactions occur during transportation in the main body, and that the flow behaves as a dilatant flow. In contrast, non-cohesive particles are less concentrated, and coarse clasts are not included in the tail or inter surge part of the flow. The flow behavior of this part shows Bingham plastic flow (Suwa and Okuda, 1985), but a rigid plug is not recognized. There is thus a difference in flow behaviors between the main body and tail in a flow, and this would be deeply related to the ability to support non-cohesive particles (Pierson, 1981).

The difference of flow behaviors would naturally influence the sedimentary features and internal structures of the products. For example, high-component flow tends to make a swollen, clast-supported debrite lobe, showing inverse grading, but a low-component flow would make a flat shaped, matrix-supported debrite lobe (Suwa and Okuda, 1985).

4.2 Coarse clast dominant conglomerate (CDC)

Even taking into account that compaction reduces the final amount of identifiable matrix, it is seen that the matrix of the CDC is less than that judged necessary for a debris flow exhibiting Bingham behavior. The typical sedimentary features and structures of the CDC strongly suggest the presence of active clast-to-clast interactions during transportation. For examples, 1) the CDC shows a massive and structureless, as well as inverse grading in the basal part, and this structure seems to be similar to a grain flow deposit (Lowe, 1976). 2) Mud and stones thrown into the air are observed in modern subaerial debris flows under the conditions of active clast-to-clast interactions (e.g. Pierson, 1981); thus, the presence of dropstone-like clasts suggests that active clast-to-clast collisions occurred repeatedly during transportation. 3) The bed morphology and the development of wet-sediment deformation in the turbidite beds beneath the CDC suggest that an abrupt deposition had occurred as a result of increased friction due to the high concentration of clasts.

In contrast, there are no large clasts that were floating within the muddy matrix, and no clumps of clasts resulting from rigid-plug transport of debris as in the Bingham behavior. Excess pore water pressure is considered not to be important in the transport of CDC. Hiscott and James (1985) pointed out that excess pore water pressure of a debris flow would probably be greatest in the basal zone. The basal zone of the debrite, however, is composed chiefly of coarse-grained materials that would make a coarse framework
structure, so it would likely be difficult for excess pore pressure to remain in the basal part for very long.

These facts suggest that clast-to-clast interactions would effectively operate as a clast-support mechanism; thus, I believe that the CDC is the product of a coarse-grain dominant debris flow with dilatant behavior.

4.3 Slurry sandstone (SLS)

SLS is interpreted to be the product of a debris flow, because of the presence of abundant muddy materials and its lens-shaped sedimentary body without major erosion, the absence of any indication that the flow was turbulent, and because of the development of internal sedimentary structures showing traction. Compared with many examples (e.g. SHARP and NOBLES, 1953; CURRY, 1966; CITTA et al., 1982), the SLS looks quite similar to the Slurry Sandstone described by HISCOTT and MIDDLETON (1979), that is interpreted to be on the order of 10^2 dynes/cm^2 in the matrix strength. I believe that the strength of SLS is comparable to that of the previously described Slurry Sandstone. The absence of large clasts, up to 5 cm in diameter, support this interpretation.

Judging from the occurrence of SLS mentioned above, its emplacement is likely to be closely related to that of the CDC. There are two possibilities to account for the SLS. One is that it is a product of entrained layers, or dilute flow, of the coarse-grain dominant debris flow which emplaced the CDC. The alternative is that the SLS was emplaced by the muddy flow part, such as the tail or intersurge flow, of the coarse-grain dominant debris flow. As the density and viscosity between the overlying seawater and the coarse-grain dominant debris flow differ, the development of entrained layers or a dilute flow can be speculated. However, the evidence for this is largely negative, because the SLS is structureless and lacks any indication (except for a very small amount of crude laminations) that the flow was tractive or turbulent, as would be expected in an entrained layer or dilute flow. In contrast, the presence of a muddy flow in a coarse-grain dominant debris flow can be predicted from subaerial and experimental examples (e.g. PIERSON, 1980). Therefore, I believe that the SLS would be the product of the tail or intersurge flow of the coarse-grain dominant debris flow which emplaced the CDC (Fig. 10).

5. Initiation of Debris Flow

Modern subaerial examples in Japan, where geologic, topographic and hydrometeorologic conditions combine to annually generate a catastrophic debris flow, show that a debris flow of dilatant behavior could produce coarse clast dominant debrisites (boulderly debrite) (e.g. TAKAHASHI, 1981; SUWA and OKUDA, 1982; SUWA et al., 1984).

Based on TAKAHASHI (1981), the theoretical conditions for the initiation of a coarse-grain dominant debris flow is shown below:

\[ \tan \theta = \frac{C_s (\sigma - \rho)}{C_s (\sigma - \rho) + \rho (1 + h_0/d)} \tan \phi \]

where \( \sigma \), \( \rho \) and \( d \) are the density of non-cohesive particles, the density of the fluid, and the representative grain size, respectively. \( \phi \) is the angle of repose. The thickness of incipient flow is \( h_0 \), so \( h_0/d = 1.4 \) is assumed as a reasonable value obtained from the experiments (TAKAHASHI, 1977). However, it would be expected to be higher in a submarine environment, so that a large degree of uncertainty would be introduced into the calculation. \( \sigma \) and \( \rho \) are 2.6 g/cm^3 and 1.1 g/cm^3, respectively, and \( \tan \phi \) is approximately 0.8. The initial
Fig. 10. Schematic reconstruction of a submarine coarse-grain dominant debris flow and its products. A: Schematic longitudinal profile of coarse-grain dominant flow modified from an subaerial example (SUWA and OKUDA, 1985). Main body behaves as a dilatant flow, but the tail part is to behave as a Bingham flow. B: Schematic sedimentary features and structures of the products of a coarse-grain dominant debris flow. Noteworthy is that sedimentary features and structures of the deposits from the main body and tail are quite different from each other.

slope gradient causing the debris flow is $\theta$. $C_s$ is the concentration rate of non-cohesive particles in the mother beds. Here, 0.7 is adapted as $C_s$, because subaerial examples show that a coarse-grain dominant debris flow is likely to originate from poorly-sorted materials (TAKAHASHI, 1977). Approximately $13^\circ$ can be calculated as the slope gradient. Experimental results (TAKAHASHI, 1977, 1980; MIZUYAMA, 1980) indicate that coarse-grain dominant flows would behave as “density-modified grain flows”, if the slope gradient were below the calculated value. Thus, it can be understood that this is a critical minimum value to produce a subaqueous coarse-grain dominant debris flow. In fact, the most modern subaerial coarse clast dominant debrizes flowed down steep slopes at their outsets (e.g. SUWA et al., 1984; CLAQUE et al., 1985).

This value is seen to be unusually steep in the modern deep sea environment, but the result of field observations that postulate that a fault escarpment developed in the debrize deposition support this estimation. The field evidence is as follows. 1) The debrizes extend approximately 30 km from Teuchizawa to Nanbu, over different stratigraphic horizons, between the Minobu and Akebono Formations. The transport direction of the debrizes is supposed to be eastward, and there are some differences in dominant clast composition, which is basalt at Teuchizawa, but andesite in the Taira and Nanbu (Fig. 2). This suggests that the debrizes are provided from a line source rather than from a point source. 2) Compared to many examples (e.g. SHARP and NOBLES, 1953; CURRY, 1966, CITAR et al.,
1982), it is likely that the clast size of debrites in the study area is coarser and more poorly-sorted than most. However, a modern example from Mt. Thomas, New Zealand, described by Pierson (1980) could be comparable. He pointed out that such clast size variation would be caused by tectonic crushing in the province. 3) Fractures and veins are developed in the clasts. 4) The boundary demarcating the two domains is shown by the Minobu Fault, thus it is possible to suppose that the fault had acted during the debrite deposition (e.g. Kimura, 1969 MS).

6. Conclusion

It is revealed that several modern examples of failures and collapse have take place on slopes with angles below the ultimate or least slope (e.g. Coleman and Prior, 1980), and this suggests that the initial conditions for failure and collapse are not only related to the slope gradient instability. The study of soil mechanics anticipates that a steep slope gradient, a decrease of material cohesion and a high pore pressure provoke floor instability (Terzaghi, 1925). It is also known that natural gas would contribute to the increase of excess pore pressure, especially in a marine environment (Coleman and Prior, 1980).

To understand the main cause of ancient failures is an interesting problem for basin analysis and the reconstruction of tectonic movements. The important clue in resolving the problem might be preserved in chaotic deposits, which would affect the initial failure conditions such as material composition, grain and/or clast size distribution, and sedimentary structure. The products of debris flows on alluvial fans (e.g. Shultz, 1984), fan-deltas (Postma, 1984) and in deep-water settings (Hill et al., 1982; Hiscott and James, 1985) are occupied mostly by matrix-supported pebbly mudstones. It can be well-explained that pebbly mudstones would be produced by a debris flow showing Bingham plastic behavior. The clast-supported coarse-grain dominant debrite, however, predominates over the present study area. This is unique and it cannot be compared to most debrite in other environments. To account for the sedimentary properties of the debrite, floor instability caused by a fault movement would be the best model, as discussed above. I believe that the presence of coarse-grain dominant, clast-supported debrite could become a good geologic indicator for floor instability caused mainly by fault movement.

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