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SEDIMENTARY MACRO-STRUCTURES AND FORMING MECHANISM OF DEBRIS FLOW

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ABSTRACT: The discussion on sedimentary macro-structures and their forming mechanism of debris flow is based on the data of present processes and ancient deposits of Dongchuan in Yunnan Province, Wudu in Gansu Province and Fuxin in Liaoning Province. Non-cohesive debris flow, which is 1.3-1.7 t/m^3 in density, follows hydraulic fluid and granular flow model. In the hydraulic fluid of flood, electrolytic water combines clay into pulp to transport solid debris. The sedimentary structures show fluid processes as stone-line structure, imbricated structure and stone supporting-superimposed structure. A part of non-cohesive debris flow with a density of 1.7-1.9 t/m^3 follows granular model. Debris is in the action of friction, collision and dispersion which forces coarse debris moving upward to form reverse graded load. The sedimentary structures of granular flow show reverse graded bedding, reverse-normal graded bedding, imbricated vertical structure and circling linear structure. Cohesive debris flow, which is 1.9-2.3 t/m^3 in density, follows structural two-phase flow (viscoplastic) model. The sedimentary structures of cohesive debris flow show reverse graded-chaotic structure, bottom mud-chaotic structure and outwedging structure.

KEY WORDS: debris flow, sedimentary structure, forming mechanism

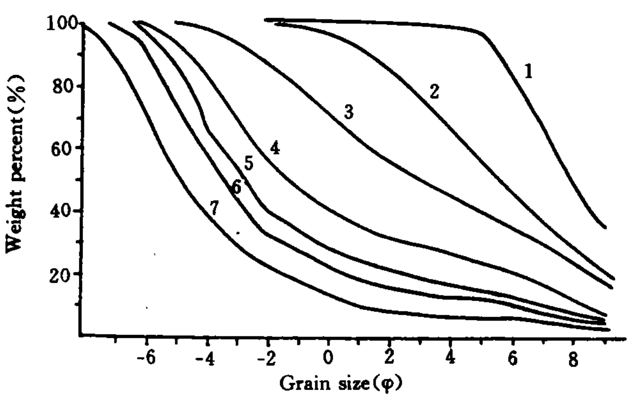
1 INTRODUCTION

The sedimentary characteristics of debris flow can reflect the composition, fluid type and sedimentary process. The scholars who study modern debris flow in China generally classify debris flow by the method of viscosity with flow pattern. Several typical schemes are shown in Table 1, in which the method of unit weight (fluid density in unit volume t/m^3) is used and fluid unit weight is thought to be the direct proposition to the viscosity of debris flow (Wu, 1990). It has been proved by hydro-mechanics that non-cohesive debris flow follows Bagnold granular flow model (Bagnold, 1956; Middleton, 1976; Lowe, 1982), cohesive debris flow follows solid-liquid structural two-phase viscoplastic model (Wang *et al.*, 1991) and transitional debris flow also follows granular flow model. Non-cohesive debris flow is called water-stone and gravel flow in some documents. A special debris flow, which is composed of water, silt and clay called mud flow, follows Bingham model and is a typical viscous fluid (Wu, 1990). The grain-size composition of debris flow is a good reflection of its fluid type and dynamic process (Fig. 1).

The authors have investigated ancient debris flow to the coal beds of the Mesozoic Era at Fuxin in Liaoning Province. Field works had been conducted in mountain areas where modern debris flows broke out frequently at Beijing, Dongchuan in Yunnan Province and Wudu in Gansu Province. The direct observation of present process and sedimentary characteristics of debris flow laid the foundation of the relationship between sedimentary structures and forming mechanism in those regions where modern debris flows are widely distributed.

Table 1 Practically adopted types of debris flow (t/m³)

Type	Tang Bangxing 1981	Wang Yuyi 1981	Zhang Xinbao 1981	Fleshman 1986	Yuan Jianmo 1986
Flood		1.02 - 1.35	1.00 - 1.35		<1.3
No-cohesive debris flow	1.3 - 1.8	1.35 - 1.69	1.26 - 1.69	1.2 - 1.5	1.3 - 1.7
Transitional debris flow	1.8 - 2.0	1.69 - 1.94	1.50 - 1.94		1.7 - 2.0
Cohesive debris flow	2.0 - 2.2	1.89 - 2.24	1.63 - 2.24	1.4 - 1.9	2.0 - 2.2



1 alluvial, 2 non-cohesive, 3 transitional, 4,5,6 cohesive, 7 debris of resource

Fig. 1 Grain size accumulative curves of debris flow at Jiangjia Valley, Dongchuan, Yunnan

2 SEDIMENTARY MACRO-STRUCTURES OF DEBRIS FLOW

The sedimentary macro-structures of debris flow mentioned here mean the features shown through arrangement and combination of composition (grains) in space.

2.1 Non-cohesive Debris Flow

Non-cohesive debris flow is characteristic of those as follows: (1) The content of the water is far higher than that of the debris in fluid; (2) The disperse agent which transports coarse debris is pulp with high density; (3) Turbulent flow is very evident when debris flow moves (Wu, 1990; Fleshman, 1978).

Coarse debris is deposited firstly when non-cohesive debris flow moves on a fan or gentle slope, pulp continues to flow then and deposits on more gentle slope or becomes current flow with sand after entering the major river. Coarse gravel deposits as a ridge along the flow direction. The major axes of coarsest gravel in intermediate zone on the fan parallel with flow direction and those at both sides of the fan intersect with flow direction at an acute angle. The gravel ridge forms stone-line structure (Wu, 1990) in profile when it stretches longitudinally, it appears as a lens horizontally. The debris flow, which is characteristic of strong turbulence, erodes river bottom and forms dissection-aggradation structure. The gravel deposit often emerges as imbricated structure and their flat planes dip upstream. There is a very evident deposit differentiation in size of non-cohesive debris flow from upstream to down stream. The fine substances form sheet-like surface mud bedding generally, or waved oblique bedding and paralled bedding at downstream. The main sedimentary macro-structures of non-cohesive debris flow are as following:

Stone-line structure. It is a typical macro-structure of non-cohesive debris flow (Fig. 2a). The stone-line structure, which is formed by gravels, stretches for decades or hundreds of meters as a ridge or ridges along the flow direction. These gravels do longitudinally in a linear manner on the primitive ground surface and their sizes are a little smaller downstream than those upstream. The flat gravels form evident imbricated structure with a gentle upstream dipping angle. There is an erosion surface at the bottom of the gravels. The gravels appear as a lens horizontally with undulated top and bottom surfaces.

Imbricated structure (Fig. 2b). It often appears in non-cohesive debris flow, in which the flat plane of the gravels dip upstream, its difference from alluvial gravels is no sorting, no abrasion and no evident

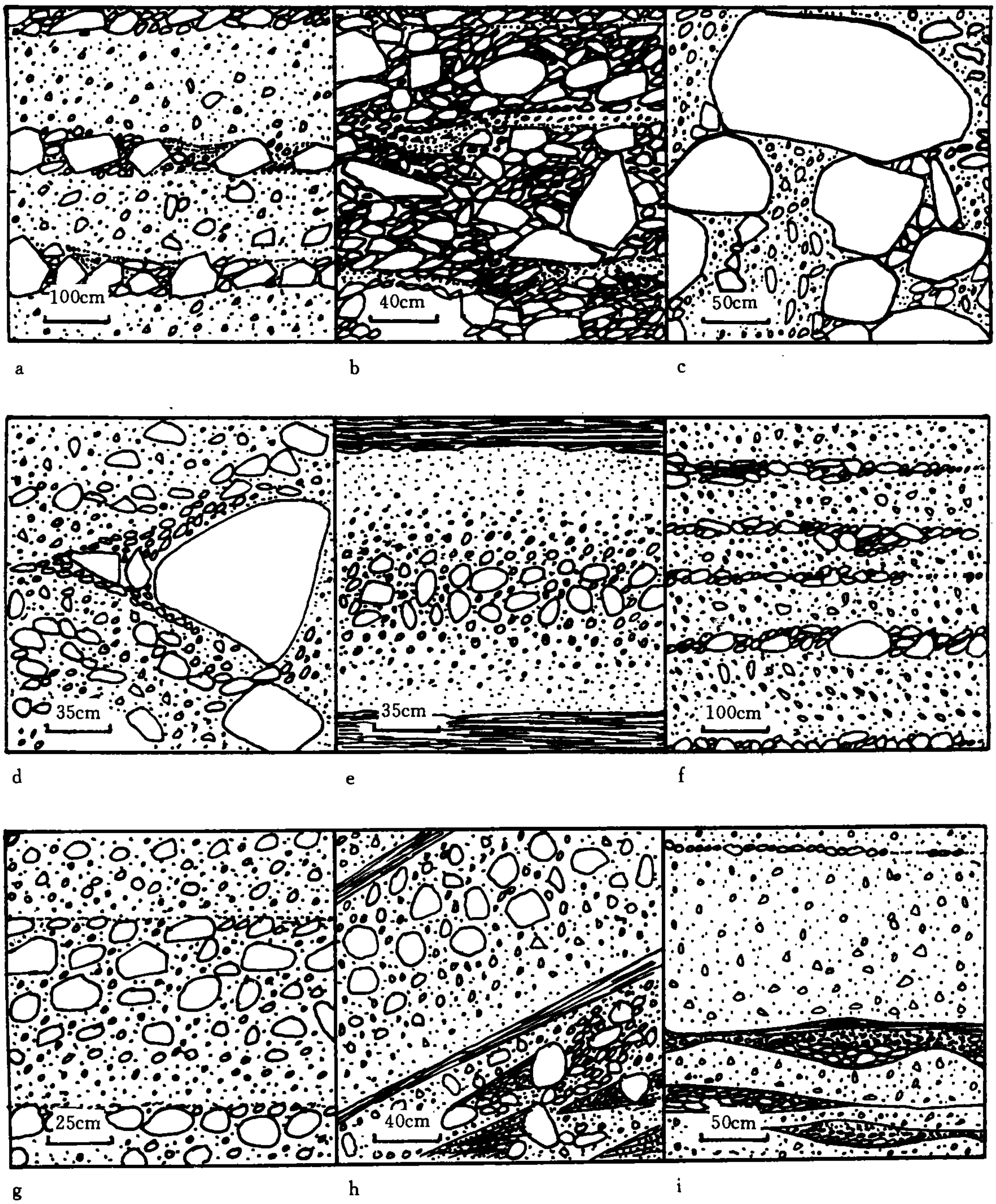


Fig. 2 Typical sedimentary macro-structures of debris flow

a. stone-line structure, b. imbricated structure (Dongchuan), c. stone supporting superimposed structure (Dongchuan), d. circling-flow structure (Dongchuan), e. reverse-normal graded bedding (Fuxin, Liaoning), f. imbricated-vertical structure (Fuxin, Liaoning), g. reverse-graded bedding (Dongchuan), h. reverse graded-chaotic structure (A) and scour bed with sand wedge of oblique bedding (B), i. chaotic structure(Dongchuan).

orientation basically in debris flow. In addition, both the top and bottom surfaces of non-cohesive debris flow which forms imbricated structure are undulate with rich coarse gravel.

Stone supporting-superimposed structure. Because of weak transport capacity on the fan, non-cohesive debris flow unloads coarse debris quickly and fine substances continue to flow. The coarse gravels, which deposit firstly, often form stone supporting-superimposed structure (Fig. 2c). The sedimentary structure mainly appears above and near the confluence of fluvial fan. The gravels resulting in the structure form sieve deposit in which evident imbricated structure can be seen.

Massive surface mud bed. It is the deposit of fine pulp separated from debris flow, forms sheet-like deposit below the confluence on the fluvial fan. The massive or normal graded structure is very evident in surface mud bed because of high content of debris and quick deposit.

2.2 Transitional Debris Flow

The deposit of transitional debris flow appear as a finger or tongue form and its thickness becomes thinner at the tail upper stream than that at the head of down stream. There is a steep ridge formed by coarser gravels at the border of the deposit. The gravels are arranged in an imbricated manner along longitudinal section and their flat planes dip upstream or in the direction of major flow line, which form ring-shaped flow-line structure (Cui, 1986). The flat gravels form centripetal (or synclinal) structure along the cross section. Fluid differentiation occurs in the course of debris flow, so fine pulp overflows upward or laterally but coarse debris submerges. The grain size decreased upward (normal graded bedding) appears in deposit.

The outflowing of the pulp forms mud-sand layer which is distributed around the major deposit. The part which loses fine pulp at the bound of the deposit becomes a coarse gravel ridge, in which the fluid keeping the primitive composition shows a normal graded bedding filled by mud. The feature of gravel fabric can be found in Fig. 3. Transitional debris flow doesn't scour bottom bed and its top surface is flat. The transitional debris flow, which is characteristics of high viscosity and relative sorting, often forms reverse graded bedding at the bottom, normal graded bedding on the top and reverse-normal graded bedding. The main sedimentary macro-structures of transitional debris flow are as follow.

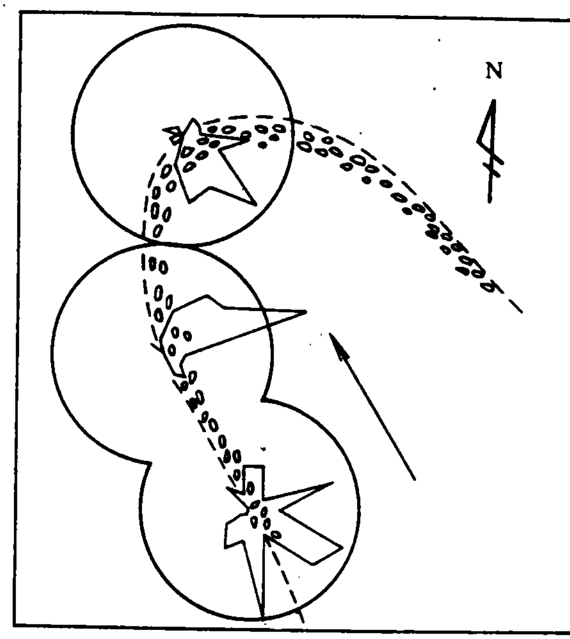


Fig. 3 Fabric of gravel dips in a tongue form debris flow (Dongchuan)

Ring-shaped flow-line structure. It is an oriental structure formed by the gravels squeezed and sheared at the border of debris flow when deposits accumulated. The flattest plane of the gavels dip along the direction of the major flow line and form circling flow structure because of different movement among different gravel sizes (Fig. 2d).

Reverse-normal graded bedding. It is the sectional feature of transitional debris flow. The normal-graded bedding at the top is result from gravitational action, while the reverse graded bedding at the bottom is formed by the shear of layer flow and grain collision (Fig. 2e).

Embricated-vertical structure. The dip angle of the flat plane of gravel in transitional debris flow, which contain a great many flat gravels and has high unit weight, increases gradually upward from basal part and even becomes vertical on top part of a debris flow deposit layer. The structure results from strong shearing of the grain at the bottom as velocity gradient is great, and supporting of structural force of the fluid as the shear force is reduced on the top. The normal graded bedding is shown in the whole section (B in Fig. 2f). The grain-size of transitional debris flow is similar to the source area, but slight variation make them different as they deposit (Fig. 1 and Fig. 2a).

2.3 Cohesive Debris Flow

The typical features of cohesive debris flow are (1) water and debris which combine in a manner move massively; (2) no free water exists; (3) it follows two-phase flow model (Wang, 1991). Based on field observation and experiment, it is shown that the flow pattern of cohesive debris flow varies from laminar flow, plug flow to plastic slide flow as its unit weight is increased and its viscosity is strengthened (Wu, 1990). Wang Yuyi *et al*. (1981) point out that pockmarked surface will appear on the deposit when density is around 2.163 t/m^3 because of stress reduction, a honey comb-like or ring-shaped surface in debris flow will form respectively as the corre sponding density is around 2.228 t/m^3 and 2.299 t/m^3. There are steep edge ($49° - 57°$), tongue form feature, flat top surface, no eroded bottom surface and shield-like cross section in cohesive debris flow deposit. Because of spasmodic squeeze, ring-shaped surface ditches and ridges appear on the head of the deposit on the fan, meanwhile gravels are oriented in the section and ring-shaped flow-line structure is formed (Fig. 3). The deposit at the intermediate zone or at the head is thicker than that at the border or at the tail. Velocity gradient is so evident at the bottom in some cohesive debris flows as they move that reverse graded bedding or bottom mud bed are formed at the bottom (Cui, 1986), however flow core in which no velocity gradient exists on the top forms chaotic bed. Reverse-graded-chaotic structure or bottom mud bed-chaotic structure of cohesive debris flow is formed by the combining of the two beddings mentioned above (Collinson *et al*., 1983). The major sedimentary macro-structures of cohesive debris flow include as follow.

Ring-shaped flow-line structure. It is the plane feature and results from the squeeze and shear of spasmodic flows.

Reverse-graded bedding. It is the sectional feature and formed by the shear of lamilar flow (Fig. 2g). The dip angle of flat gravels gradually increases from the bottom to the top and the gravels are supported by mud matrix (layer D, F, H, J in Fig. 2f).

Reverse-graded-chaotic structure. The structure is composed of a lower reverse-graded bedding and a upper massive chaotic bedding (Fig. 2h) with mud matrix support. Parallel bedding or gentle waved bedding appears in the base of reverse-graded bedding sometimes.

Chaotic structure, bottom mud bed-dhaotic structure (Fig. 2i). They appear in high viscosity debris flow, which is characteristic of no sorting, no abrasion and no bedding. The bottom mud bed, which can be found at the bottom of massive muddy conglomerate, stretches gently on a non-eroded bed. Chaotic structure and bottom mud-chaotic structure appear evidently in the cohesive debris flows with an unit weigh of 2.20 t/m^3 in modern debris flow area in Jiangjia Valley, Dongchuan, Yunnan Province.

Wedge structure. It is a flank changing form in the section of cohesive debris flow (Li, 1988). The debris flow layer varies in an abrupt wedged manner either in vertical or in paralleling to the flow direction. It is the reflection of structural debris flow(Wu, 1990), which can keep a steep edge.

2.4 Summary of the Sedimentary Macro-structure of Debris Flow

The typical sedimentary macro-structures of noncohesive debris flow are stone-line, imbricated, stone supported-superimposed structures and massive mud bed. The major macro-structures of transitional debris flow include ring-shaped flow-line structure, reverse-normal graded bedding, imbricated-vertical structure. The typical sedimentary macro-structures of cohesive debris flow are ring-shaped flow-line, reverse graded-chaotic, bottom mud-chaotic, chaotic and wedged structures.

3 DISCUSSION OF FORMING MECHANISM OF THE SEDIMENTARY STRUCTURES

3.1 Grain-size Composition and Fluid Characteristics

The grain-size composition mainly reflects the debris component in the primitive source area and is also related to transporting process (Wu, 1990; Zhang *et al.*, 1981). The differentiation of the grain-size is very evident in the course of deposit of non-cohesive debris flow. Coarse debris deposits firstly and fine pulp deposit downstream on the fan or becomes turbulent flow with sand entering the major river. Therefore, the grain-size composition of non-cohesive debris flow deposit does not reflect the grain-size composition of debris flow in movement and the grain-size curve is more similar to that of the turbulent flow (see 2 in Fig. 1; Wu, 1990). The limited grain-size sorting in the deposit of transitional debris flow and its grain-size curve are between those of turbulent flow and debris in primitive source area (see 3 in Fig. 1). Massive transportation and deposit occurs in cohesive debris flow and the grain-size composition is very similar to the primitive source area (see 4, 5, 6 in Fig. 1). Several peaks appear in the frequency curve (Fig. 4), this reflect the debris features in the primitive source area. The structural type and intensity of the fluid is related with the content of clay mineral, so is the unit weight of fluid (Wu, 1990). The higher the content of clay mineral and unit weight is, the greater the intensity of the fluid will be, the more strengthened the capacity of suspending and transporting coarse gravels will be.

3.2 The Transporting Mechanism of Debris Flow

Non-cohesive debris flow has a unit weight of 1.3 – 1.7 t/m^3 and follows the flood-grain flow model. The electrolytic water and clay form the pulp, which transport silt, sand and gravel. Both the size and the content of the debris are reduced upward quickly. The sedimentary structures which can reflect the fluid feature include stone-line, imbricated, stone supporting-superimposed structures. The non-cohesive debris flow and the transitional debris flow follow grain flow model, in which water, silt and clay can not make the pulp strong enough to form structural force (Bagnold, 1956; Middleton and Thompson, 1976; Lowe, 1982). The debris is in action of friction, collision and dispersion which forces coarse debris to move upward, resulting in reverse-graded bedding as the top dispersion force is reduced, and normal-graded bedding will form. Therefore the sedimentary structures which reflect the fluid characteristic in non-cohesive and transitional debris flows are reverse-graded bedding, reverse-normal graded bedding, imbricated-vertical and ring-shaped flow-line structures. Cohesive debris flow has a unit weight of 1.9 – 2.3 t/m^3 and follows structural two-phase flow (Wang *et al.*, 1991). Water and fine debris in the fluid compose the pulp with regular structure and the coarse debris keeps in solid phase. The given structural fluid formed by pulp combining with coarse debris again in

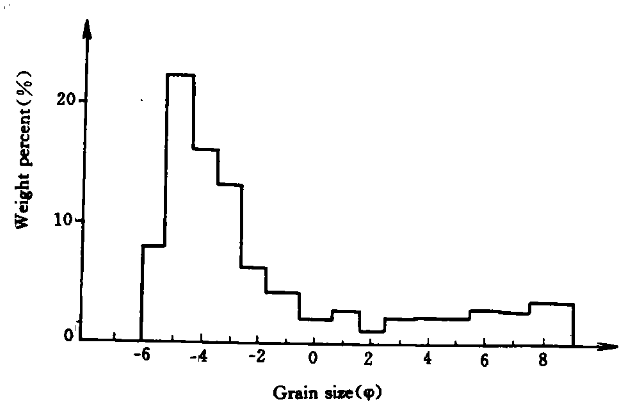


Fig. 4 Frequency curve of grain-size of cohesive debris flow in Jiangjia valley, Dongchuan, Yunnan Province

movement of debris flow causes a massive transportation (Wu, 1990). The evident differentiation of size and content of debris flow from bottom to top does not occur as debris flow moves, but its velocity gradient varies evidently. The sedimentary structures which reflect the fluid feature are reverse-grade-chaotic structure, bottom mud-chaotic structure and wedged structure (Li, 1988).

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