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Research Article

Jinyu Tao*, Changmin Zhang, and Rui Zhu

Gravel roundness quantitative analysis for sedimentary microfacies of fan delta deposition, Baikouquan Formation, Mahu Depression, Northwestern China

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Abstract: Gravel roundness is one of the simple but crucial parameters in particle shape, which is related to the transportation and deposition of sediments. Based on the digital images of underground drilling cores, this study attempted to characterize and distinguish sedimentary microfacies by quantitatively test gravel roundness trends in the fan delta deposition of the Early Triassic Baikouquan Formation in Mahu Depression, Juggar Basin of China. By the new proposed de-flat roundness measurement, two major parameters are recorded to manifest the rounding degree, which is de-flat roundness value (Rd_n) and the corresponding variance value. In the case study, roundness characteristics of four microfacies in the fan delta deposits are displayed and compared. Results show that braided channels and submerged distributary channels are characterized by better rounding (Rd_n 0.379 to 0.603, and 0.366 to 0.591, respectively) and smaller variance, while debris flow and submerged debris flow are characterized by worse rounding (Rd_n 0.333 to 0.405 and 0.256 to 0.391, respectively) and larger variance. In vertical of the roundness curves, channels deposits and gravity flow deposits reveal notable distinction in terms of the numeric ranges, fluctuation amplitude, and fluctuate frequency. It is interpreted to represent the different sedimentary processes during particle transport and deposit, as well as new clastics mixed in from other sources. Therefore, roundness could be a useful complementary data to provide quantitative sedimentological evidence and theoretical support for the study of coarse clastic depositional system.

* **Corresponding author: Jinyu Tao,** Wuxi Institute of Petroleum Geology, Petroleum Exploration and Production Research Institute, SINOPEC, 2060 Lihu Avenue, Binhu District, Wuxi, Jiangsu 214126, China; School of Geosciences, Yangtze University, Caidian District, Wuhan, Hubei 430100, China, e-mail: glamoureileen@163.com
Changmin Zhang, Rui Zhu: School of Geosciences, Yangtze University, Caidian District, Wuhan, Hubei 430100, China

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1 Introduction

Roundness, as one of the important parameters of particle morphology, represents the rounding degree of original grain edges and corners [1–3]. In different sedimentary environments, the roundness shows different characteristics [4–6]. For example, gravels deposited on the coast are washed repeatedly by the waves, so they can be very rounded [7,8]. The morphology of moraine, without modified by glacial meltwater, reflects the nature of its parent rock. The detrital particles in the river undergo continuous traction flow transport, yet with different erosion and abrasion duration. It leads to the fact that these particles in the river may not share the same rounding characteristics in upstream and downstream of the channel [9,10]. Thus, in geosciences, particle roundness records the process of abrasion and re-transportation of the clastics [11,12], which keeps an important relationship with sedimentary hydrodynamic conditions [13,14], sediment transport distance [15,16], the origin and trace source of sediments [17–19], and even tectonic activities [20]. In addition to geology, particle roundness has been widely used in many fields such as machinery, aircraft, agriculture, and metallurgy [21–23].

Located in the northwestern of Junggar Basin, Mahu Depression is one of the key areas for petroleum and gas exploration in China [24], of which the discovered petroleum and gas reserves have exceeded 1 billion tons by 2017. The main oil-bearing members in Mahu Depression must be the Triassic Baikouquan Formation (T_1b), which is deposited by a set of thick conglomerates [25,26]. However, in the T_1b of this depression, there are still some disputes about the sedimentary system of coarse-grained deposit, recognized as an alluvial fan, fan delta, or DFS (Distributive Fluvial System) [27–30]. Therefore, it is necessary to use various methods to explain the rationality of sedimentary facies in the Mahu Depression.

As we know, gravels roundness could be different in various sedimentary environment like coast, channel, desert, and alluvial fan. The question is, if gravels are from the one sedimentary system or facies with similar source rocks, will their roundness be different in different microfacies? The aim of this study is to tentatively distinguish different sedimentary microfacies of fan delta deposits by quantitative gravel roundness analysis. As for the layers abundant of conglomerates, it is suitable and convenient for visual observation of the morphological characteristics of gravel particles and easy for roundness measuring. By the de-flat roundness method proposed by Tao et al. [23], roundness characteristics of four microfacies in the T_1b fan delta deposits are displayed and compared. The study shows that roundness could be a supplementary tool for quantitative sedimentary facies analysis of coarse clastic materials.

1.1 Geologic background

The work area is located in the west slope of Mahu Depression, northwestern Junggar Basin, Xinjiang Province in Northwestern China (Figure 1). The 5,000 km^2 Mahu Depression is bounded by Shiyingtan Uplift and Yingxi Depression in the north and Zhonggua Uplift in the south, which is about 50 km E–W and 100 km N–S [28]. During the early Permian, Mahu is contained by an E–S monoclinal structure, with a relatively gentle slope [25,26]. At that time, Zaire Mountain and Halarat Mountain as the source area provided sufficient materials for the depression. Due to continuous tectonic uplift, coarse-grained fan deposits are formed near the mountains on the western slope of Mahu during Late Permian and Early Triassic [29,31].

Among the coarse-grained fan deposition, Xiazijie fan and Huangyangquan fan of Mahu Depression are the major study areas mentioned in the text (Figure 1). According to the paleocurrent data, cross-bedding attitude measuring and other mainstream provenance studies previously [32–34], it indicates that the sediments in Xiazijie fan are delivered from the north, such as the Zeil Mountain and Halarat Mountain. On the other hand, sediments in Huangyangquan fan are likely originated from the northwest, such as the Halarat Mountain and Zaire Mountain. While the sediment source of the two fans are from different directions, the key components of source rocks are similar, which are intermediate-basic

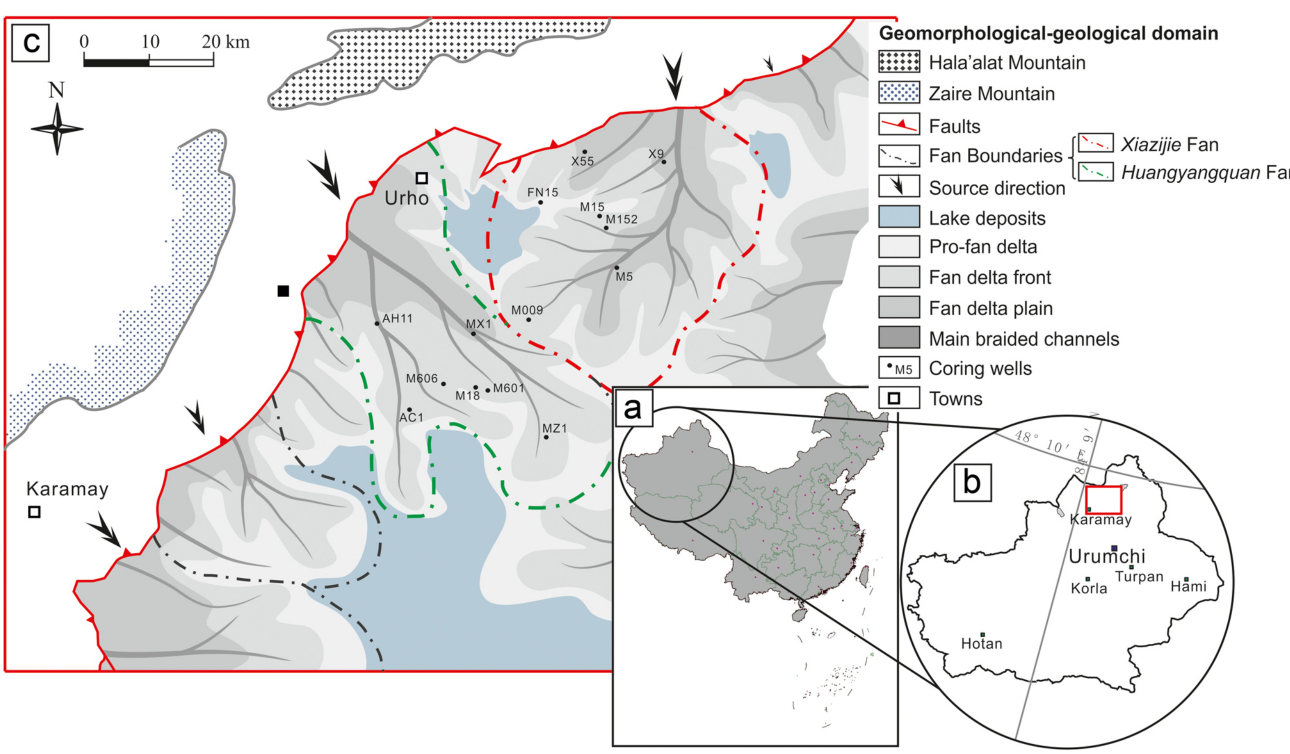

Figure 1: Location of the study area (modified after ref. [35]). (a) Large-scale map of Xinjiang Province in China. (b) The work area is located in northern Xinjiang Province. (c) Detailed map with typical coring wells location and the approximate scope of ancient fan deposits (including alluvial fans and fan deltas) in T_1b.

magmatic rocks from the upper crust. Thus, it has some points of similarity in lithological hardness and mechanical wearing, which is considered to be the precondition for the research of roundness and sedimentary facies.

The focus of this study is the Baikouquan Formation of Early Triassic (T_1b), with the underlying strata Urho Formation of Permian (P_2w) and capped by Karamay Formation (T_2k) [36]. The target layer is up to 140 m thick with an average thickness of 130 m. It is characterized by dry and hot paleoclimate with shallow water and abundant source materials. Stratigraphically, T_1b is equivalent to alluvial to fluvial–deltaic deposition upward, which is consistent with a lacustrine-transgressing sequence. The sediments in T_1b are thickly composed of gray, taupe, and grayish-green conglomerates, with the grain size of clastic particles larger than 4 mm.

1.2 Sedimentary facies in Mahu Depression

According to the observation and description of drilling cores, fan delta deposits are interpreted to be the main sedimentary facies in T_1b of Mahu Depression [37]. Eight sedimentary microfacies are identified, which are debris flow microfacies, braided channels microfacies, interchannel microfacies, submerged distributary channels microfacies, interdistributary bay microfacies, estuarine bar microfacies, submerged debris flow microfacies, and neritic shale microfacies. Among them, the first three microfacies are deposited in fan delta plain subfacies, the following four are deposited in fan delta front subfacies, and the last one is deposited in pro-fan delta subfacies.

However, not all the microfacies in Mahu Depression are contained by coarse clastics. For example, interchannel microfacies mainly consists of sandy and muddy deposit. Gravel particles in the interchannel are deposited as sheetflood, obviously less than the gravels in the channels. Thus, it is little useful for gravel roundness study.

There are four microfacies dominated by conglomerates, which are debris flow microfacies, braided channels microfacies, submerged distributary channels microfacies, and submerged debris flow microfacies. Hence, the roundness research is focused on the four microfacies.

Although the provenances of Xiazijie fan and Huangyangquan fan are similar, the sedimentary facies types between the two fans may be quite different caused by the topographic condition and fan scale. In Xiazijie fan, relatively stable channels are sustained on the fan surface, mostly braided channels and submerged distributary channels, with rare debris flow and basically little submerged debris flow. The terrain goes steep and then gentle, with the scale extended over 50 km, which seems like a strong-dynamic fluvial fan. On the other hand, in Huangyangquan fan, it ranges much smaller in the fan body size than the Xiazijie fan. Typical microfacies are debris flow and braided channels. Submerged debris flow could sometimes be discovered in the underwater environment.

2 Methods

Scholars attempted to calculate roundness by several methods, typically like the inscribed circle, the fractal dimension, the Fourier Transform, and so on [38–41]. In this study, roundness parameters are calculated by a de-flat roundness method, which was introduced specifically in reference [35]. Before the calculation, Core images in this study were collected by Canon EOS 7D camera. Image acquisition for the gravel particles is necessary by Adobe Photoshop CC 2018, which allow us to trace the particles outlines. In this chapter, the image processing and de-flat roundness method are introduced in the following sections.

2.1 Image processing and particle extraction

The aim of core images acquisition is to extract particle contour. Some professional graphics software, such as IPP6.0, ImageJ, and SAGA, can be used to automatically extract particles according to the different colors of the particle's contour boundaries [42–44]. But if cores reveal stale surface or obvious scratch, particles contours would be blurred and difficult to recognize. Thus, the "Magnetic Lasso" tool in Adobe Photoshop CC 2018 software is adopted for extraction of the visible particles. Then, extracting the gravel particles outlines images into BMP format. The examples of particle extraction are shown in Figure 2. After that, de-flat roundness data could be obtained so as to analyze the measuring results later.

2.2 De-flat roundness method

As the de-flat method is derived from the percentage roundness method, we shall explain the "percentage

Figure 2: Particle extraction process of core images by the de-flat roundness software, modified from ref. [35].

roundness" first. The percentage roundness represents the percentage ratio that the particle's area holds to the area of a circle with the same perimeter [45], which can be gained just by the particle's perimeter and area. The formula of percentage roundness is as follows:

$$\mathrm{Rp} = 4\pi A/P^2. \quad (1)$$

In formula (1), A represents the area of any given shape, P represents the corresponding perimeter, and Rp is the "percentage roundness" value, ranging from 0 to 1. The higher Rp value indicates more rounded shape.

However, in fact, the Rp is mainly expressed as the particle's shape, which is restricted by the formula itself. For example, the Rp of an ellipse is smaller than that of a perfect circle, although they are both round. The ellipse holds a smaller area than the perfect circle; thus, both have the same perimeter but an excellent roundness level. In other words, only when the shape of grains is similar can the percentage roundness be effective to judge the rounding level [35].

The de-flat roundness method is improved on the percentage roundness method. The principle of de-flat algorithm is to turn the minimum bounding rectangle (*MinBoundRect*) of a given shape into a square and then to calculate the deformed shape by the percentage roundness formula (Figure 3). In other words, it is based on image morphing, so that all shapes of particles could be standardized.

By the de-flat roundness method, the calculated result is the so-called de-flat roundness value, which is recorded as Rd. Due to the stretching of particle shape, the Rd value would be larger than the Rp value to some degrees. Lots of image tests showed that Rd values of the most particles range from 0.7 to 1. In order to conform to the traditional roundness range, which is from 0 to 1, numerical normalization of Rd values are carried out, which is recorded as Rd_n value. The following roundness values of measured particles all refer to the Rd_n values.

Based on the detailed core description, the lithofacies of conglomerates are considered as the roundness measuring unit. Lithofacies is the basic genetic unit which reveal the same sedimentary structure and lithology, reflecting specific hydrodynamic conditions [10,46–48]. Sedimentary microfacies are closely related to the characteristics of sediment color, roundness, and particle arrangement [37]. In $\mathrm{T_1b}$ conglomerates in Mahu, there are many types of complex lithologic strata, large range of grain size, and diverse sedimentary structures. In order to characterize the lithofacies in detail, a multi-attribute lithofacies naming scheme is used based on the combination of four attributes of grain size, sedimentary structure, color, and particle support mode [37], which are expressed in a unified format, like $\mathbf{A_b cde}$. Where, "A," capital English letter, represents the lithology and "b," subscript number, represents the subparticle. In conglomerates, $\mathrm{G_1}$–$\mathrm{G_5}$ represents boulders, cobbles, coarse pebbles, fine pebbles, and granules, respectively. "c," lower case letter, represents the sedimentary structures, such as massive bedding (m) and cross bedding (x). "d," lower case letters, represent the color, like grayish-green (gg), gray (g), and rufous (r). "e," roman letters, represents the particle support mode: grain support (I), multigrade support (II), matrix–grain support (III), and matrix support (IV). By the classification scheme above, lithofacies of roundness measurement are named, for example, "$\mathrm{G_4}$xgII" represents the gray fine pebbles of cross bedding, with multigrade support mode.

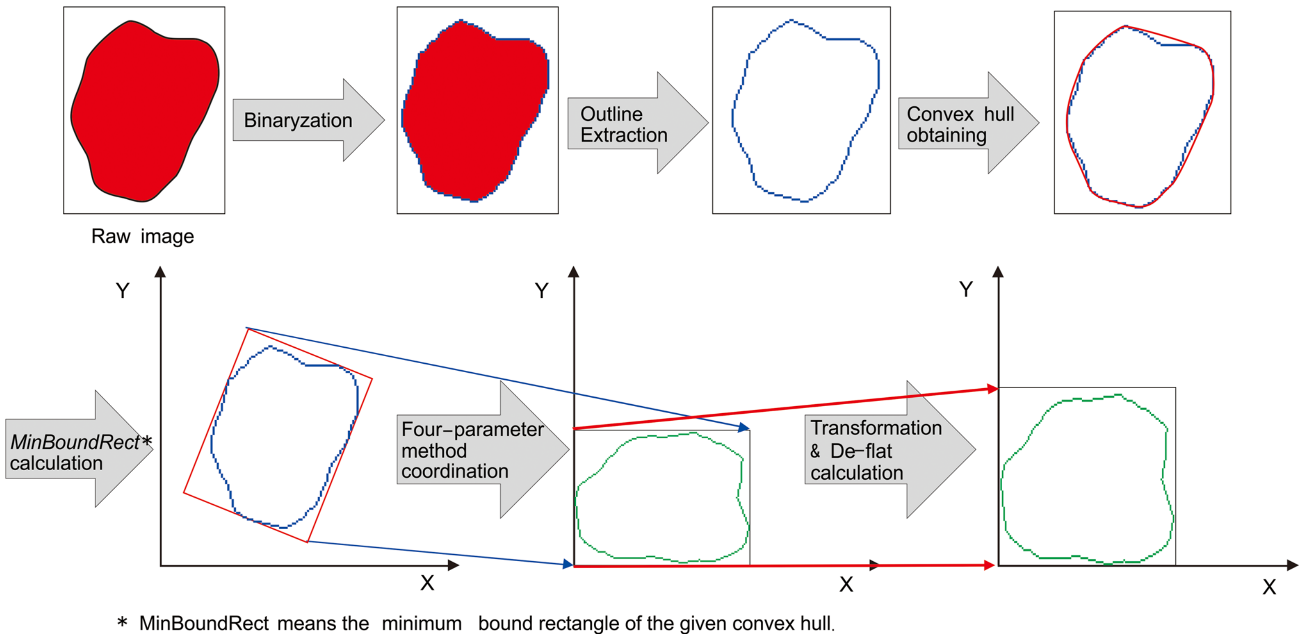

Figure 3: Basic concept of de-flat roundness, modified from ref. [4].

From the perspective of the dynamic mechanism in coarse-clastic deposits, lithofacies could reflect the sedimentary hydrodynamic conditions, so as to describe the variation of roundness. At this point, the variance of all roundness values in each lithofacies is recorded as Var (Variance), indicating the amount of roundness deviation in the lithofacies. The larger Var value means much dispersed distribution of roundness in one lithofacies, whereas means much concentrated roundness.

2.3 Discriminant standard

According to the roundness classification during observation [49] and description of drilling cores, there are 5 rounding grades in T_1b conglomerates, which are angular, sub-angular, sub-angular and rounded, sub-rounded, and rounded, as shown in Figure 4. This should be the qualitative standard of roundness, which is consistent with the conventional observations. As for the quantitative discriminant standard, 100 gravel particles of each rounding grade by naked eye estimation are collected as the test images, so a total of 500 gravel particles are collected. Then, run the de-flat roundness algorithm. The testing results of the quantile in 20%, 40%, 60%, and 80% are regarded as the threshold value of roundness, which take the numerical interval of the 5 roundness grade 0–0.4, 0.4–0.53, 0.53–0.62, 0.62–0.83, and 0.83–1, respectively (Figure 4). And this should be the quantitative standard of roundness.

3 Results and analysis

In this paper, roundness data of 296 conglomerates lithofacies from 79 wells of T_1b in Mahu Depression were measured, with 10,663 gravels extracted. An average of 36 gravels were extracted in each lithofacies. The gathered statistics include 19 lithofacies of debris flow deposits, 22 lithofacies of submerged debris flow deposits, 143 lithofacies of braided channels, and 112 lithofacies of submerged distributary channels deposits (Figure 5 and Table 1).

From the statistics, the average roundness values of debris flow and submerged debris flow are similar, 0.313 and 0.311, respectively. Referentially, the median roundness values are 0.383 and 0.325, and the Rd_n distribution range of 25 to 75% quantiles is 0.332 to 0.405 and 0.256 to 0.391, respectively. As for the braided channels and submerged distributary channels, the average values of roundness are 0.489 and 0.474, respectively. It implies a dramatic difference in gravel roundness between gravity flow deposition and channels deposition. The roundness of gravity flow deposits is generally worse than the channels deposits.

Roundness type	Angular	Sub-angular	Sub-angular & rounded	Sub-rounded	Rounded
25-75% Rd_n confidence interval	(0 - 0.40)	(0.4 - 0.53)	(0. 53 - 0.62)	(0.62 - 0.83)	(0.83 - 1)

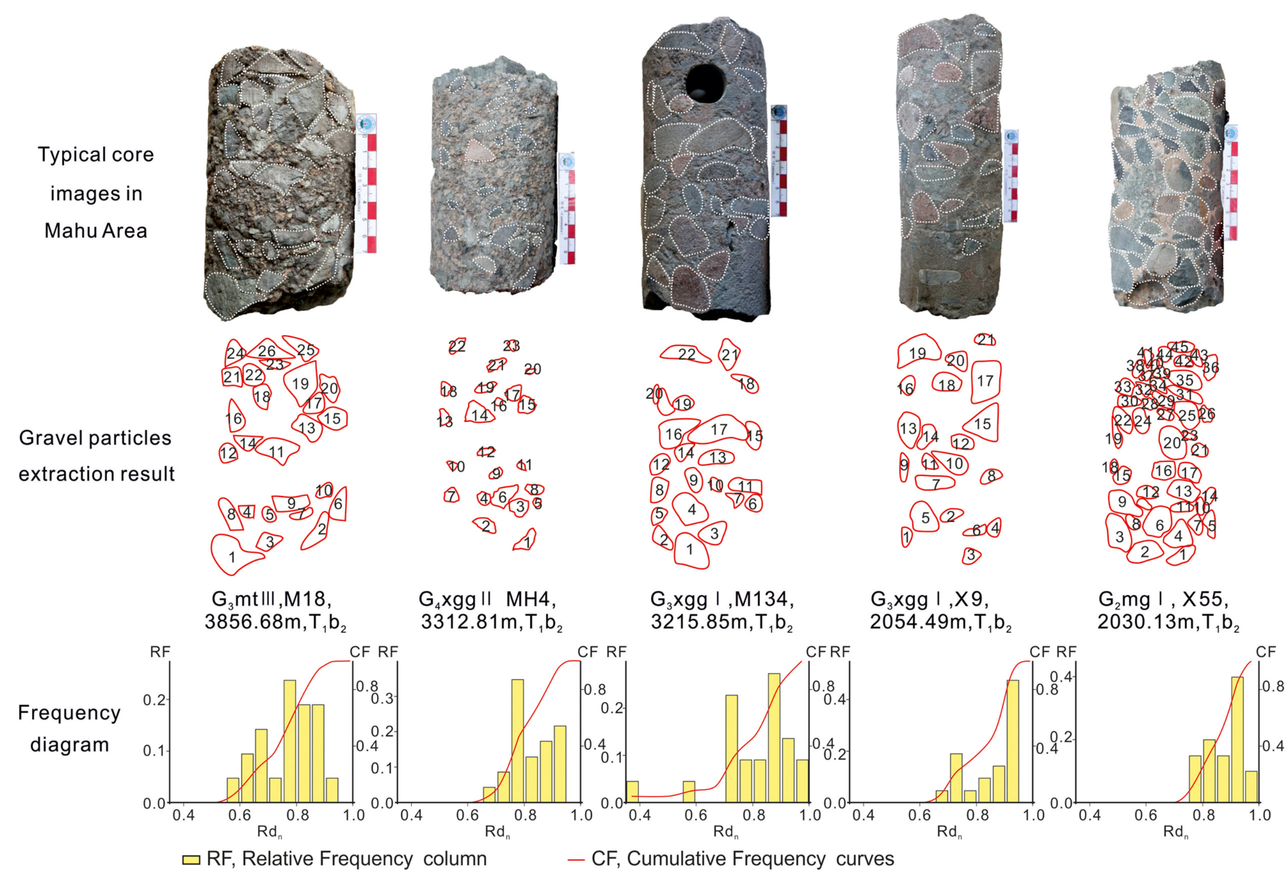

Figure 4: Quantitative standard of gravel roundness in Mahu Depression and typical cores, modified by ref. [4]. The frequency diagram represents the exampled core image for each of the five types.

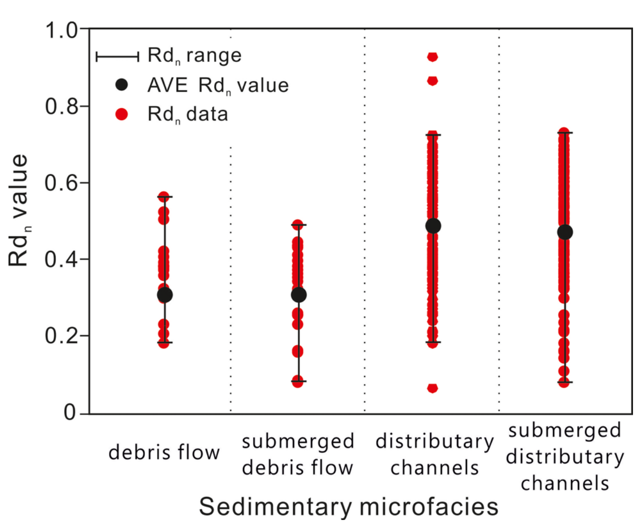

Figure 5: Gravel roundness statistical results of sedimentary microfacies from conglomerates core sections, T_1b, Mahu Area.

Based on the above statistics, comparative analyses are carried out on the gravel roundness characteristics of the four sedimentary microfacies in T_1b of Mahu Depression. The variation trend in vertical of the roundness and its variance curves are also discussed. For example, four typical core profiles are illustrated in the following sections, with the statistical data measured in Table 2.

3.1 Debris flow microfacies

When the water flow carries large amount of gravels, sands, and mud materials, a fluid form with high density, viscosity, and plasticity, known as the debris flow [50,51]. In the debris flow, sediments are massive transported on the fan delta body. In Mahu Depression, sediments in

Table 1: Gravel roundness statistics of sedimentary microfacies from conglomerates core sections, T_1b, Mahu Depression

Sedimentary microfacies	Rd_n quantile			MIN Rd_n	AVE Rd_n	MAX Rd_n
	25%	50%	75%			
Braided channels	0.379	0.503	0.603	0.070	0.489	0.927
Submerged distributary channels	0.366	0.503	0.591	0.080	0.474	0.730
Debris flow	0.333	0.383	0.405	0.183	0.313	0.564
Submerged debris flow	0.256	0.325	0.391	0.080	0.311	0.492

debris flow microfacies are composed of reddish-brown conglomerates, with pebbles and granules such as G_3xggI, G_3mrIV, and G_4mggII. The lowermost section is dominated by interbed granules and pebbles. Layers are thinner upward. Red-brown gravels are present in the uppermost layer. Particles are supported by mud, sand, and small-sized granules, which seems to be the multilevel particle support mode. In that case, the deposits are extremely poor-sorted, which reflects the massive transport and gravity flow deposition in the oxidation environment.

Table 2: Statistical table of roundness samples of sedimentary microfacies profiles

No.	Lithofacies	Depth/m	Rd_n value			$V/\times 10^{-2}$	Number of gravels
			25%	50%	75%		
1	G_5xrII	2872.10	0.459	0.563	0.744	0.56	30
2	G_3xrII	2872.40	0.097	0.530	0.800	9.19	5
3	G_3xrI	2873.05	0.423	0.617	0.757	4.10	13
4	G_3mrI	2873.75	0.308	0.537	0.634	4.84	10
5	G_3xrII	2874.15	0.480	0.580	0.643	2.12	5
6	G_3mgIII	2874.85	0.337	0.613	0.691	5.87	10
7	G_3xggII	2876.07	0.423	0.493	0.557	1.47	8
8	G_3mrIV	2876.73	0.533	0.677	0.810	3.04	6
9	G_5mrII	3311.15	0.503	0.547	0.642	0.92	15
10	G_5xggI	3311.25	0.493	0.637	0.758	3.04	23
11	G_2mggII	3311.45	0.083	0.317	0.590	4.95	19
12	S_2mr	3311.63	0.302	0.547	0.748	5.20	31
13	G_5mrII	3311.84	0.178	0.320	0.475	3.00	15
14	G_4xggI	3312.08	0.320	0.423	0.674	2.16	16
15	G_4xggIII	3312.51	0.197	0.290	0.527	1.98	13
16	G_5mggI	3312.92	0.263	0.503	0.673	5.09	23
17	G_5maI	3313.17	0.093	0.293	0.510	4.24	13
18	G_4mggI	3313.24	0.244	0.358	0.516	2.42	16
19	G_4xgI	2030.12	0.510	0.553	0.626	0.92	12
20	G_2xgII	2030.40	0.495	0.637	0.735	0.30	46
21	G_2xgI	2030.57	0.513	0.587	0.648	1.55	14
22	G_1mgI	2030.78	0.453	0.510	0.693	1.20	4
23	G_3xgI	2030.95	0.108	0.220	0.332	2.37	2
24	G_3mgI	2678.28	0.585	0.620	0.635	0.74	7
25	G_5xgII	2678.56	0.468	0.643	0.722	3.76	10
26	G_4xgI	2678.82	0.553	0.690	0.787	2.90	13
27	G_3mgI	2679.12	0.409	0.583	0.693	3.70	16
28	G_4pgI	2679.42	0.418	0.483	0.593	1.38	12
29	G_3mgII	2679.67	0.363	0.513	0.627	3.18	13
30	G_4xgII	2679.83	0.134	0.323	0.510	4.01	6

Note: debris flow samples 1–8; submerged debris flow samples 9–18; braided channel samples 19–23; submerged distributary channel samples 24–30.

The typical section of debris flow microfacies is 2872.4–2877.3 m in well AH 11. In this section, a total of 8 lithofacies were measured, with 87 pieces of gravels extracted (Table 2). The results show that the range of roundness in well AH11 section is from 0.325 to 0.690, sub-angular and rounded. The Var values are particularly high (average 0.092), which means the gravel roundness in debris flow deposition is poorly sorted.

According to the trend of gravel roundness curves and its corresponding variance curves in vertical of typical debris flow profile (Figure 6), it can be seen that the roundness of the lower part of this section is better (sub-rounded), with a slight decrease upward (sub-angular and rounded). The Var values tend to be lower (less than 0.03), which indicates the roundness values of gravel is relatively concentrated. The upper Var values increase (larger than 0.04 and as high as 0.09 at 2872.65 m), indicating that the gravel roundness is much dispersed. The variance at the top decrease sharply, with Var value only 0.0056. In conclusion, the variance curve of roundness in typical coring sections of debris flow deposition is obviously disordered. The gravel roundness is characterized as sub-angular and rounded and worse upward.

3.2 Braided channels microfacies

In braided channels, the sediments usually deposit after longer distance transport than the debris flow, with large flow and strong hydrodynamic force, which represents strong carrying capacity. Braided channels are the main driving force for sediments transport among the fans in Mahu. Conglomerates in this microfacies are composed of fine-coarse pebbles and cobbles, which suggests a fining-upwards sequence. Typical lithofacies are G$_2$xgI, G$_1$mgI, G$_3$xgI, etc., mainly gray and gray-green. There is a low content of matrix in this core section. Particles are supported each other with loose argillaceous cementation and moderate sorting.

The typical section of braided channels microfacies is the 2030.12–2030.95 m section of well X55. In this section, a total of 5 lithofacies were measured, with 78 pieces of gravels extracted (Table 2). The roundness of Well X55 section ranges from 0.387 to 0.687, gradually increasing upward. It seems to be better rounded than the debris flow microfacies section. Meanwhile, there is a low roundness variance, with the average 0.013, which indicates that the distribution of the gravel roundness in the braided channels is relatively concentrated.

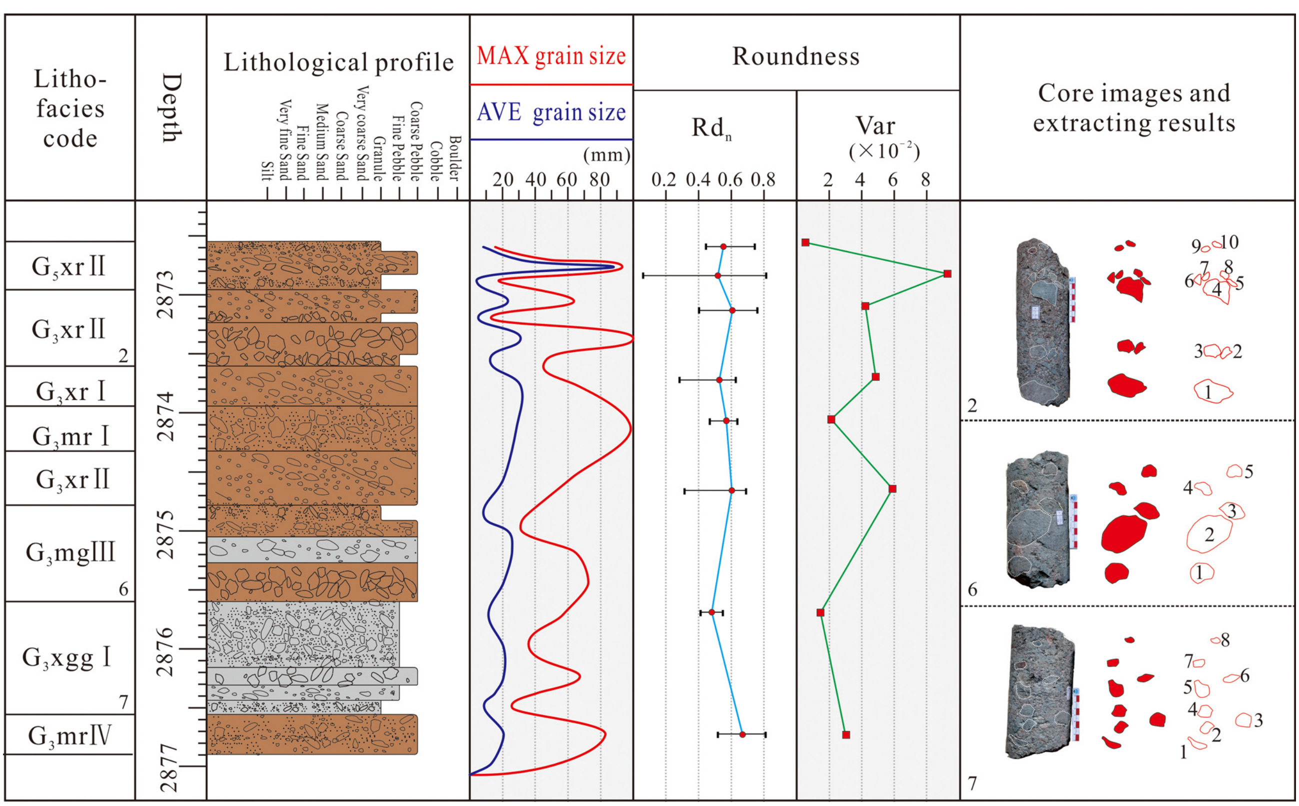

Figure 6: Roundness characteristics of typical debris flow deposit section in the Well AH11.

According to the trend of gravel roundness curves and its corresponding variance curves in vertical of typical braided channels (Figure 7), gravels are mostly angular, with poor rounding at the bottom. But it tends to be better upward, mostly sub-angular and rounded. At the top of this section, the roundness is slightly worse and sub-angular and rounded. Meanwhile, the variance of roundness is low, with a decrease upward in vertical, indicating that the roundness of gravels become more concentrated upward. Combining with other sedimentary characteristics, sedimentary structures are dominated by cross-bedding, with a set of finning-upward sequence. In summary, the gravel roundness of typical coring sections in braided channels is better upward, with smoother curves.

3.3 Submerged distributary channels microfacies

The submerged distributary channels are mainly in the front fan delta, as the extension of the braided river under water. In the core section of Mahu, the lithofacies are composed by G_3mgI, G_4xgII, G_5xgII, mainly grayish-green coarse pebbles and fine pebbles, with a finning-upward trend. Gray green, gray, red meat gravel particles are common. Medium to high content of matrix is shown, mostly fine-sand and mud. The supporting mode of gravels is the particle support, with better-sorting upward. In vertical, sedimentary structures in this section vary from massive structure to bedding structures upward.

The typical section of submerged distributary channels microfacies is 2678.14–2685.58 m in well FN 15. In this section, a total of 7 lithofacies were measured, with 77 pieces of gravels extracted (Table 2). The roundness of most gravels in well FN 15 section is sub-angular and rounded, with better rounding upward. The Rd_n values range from 0.323 to 0.690. Var values are low, with the average 0.028 and decreasing upward, which indicates that the distribution of gravel roundness in the submerged distributary channels is much concentrated upward.

According to the trend of gravel roundness curves and its corresponding variance curves in vertical of typical submerged distributary channels (Figure 8), gravel roundness at the bottom is poor, mostly angular. The upper part is becoming better rounding, sub-angular and rounded, and sub-rounded. Two cycles of roundness fluctuating sections could be identified at the depth of 2678.14–2679.72 and 2679.72–2679.98 m. It reflects twice roundness changing from dispersion to concentration,

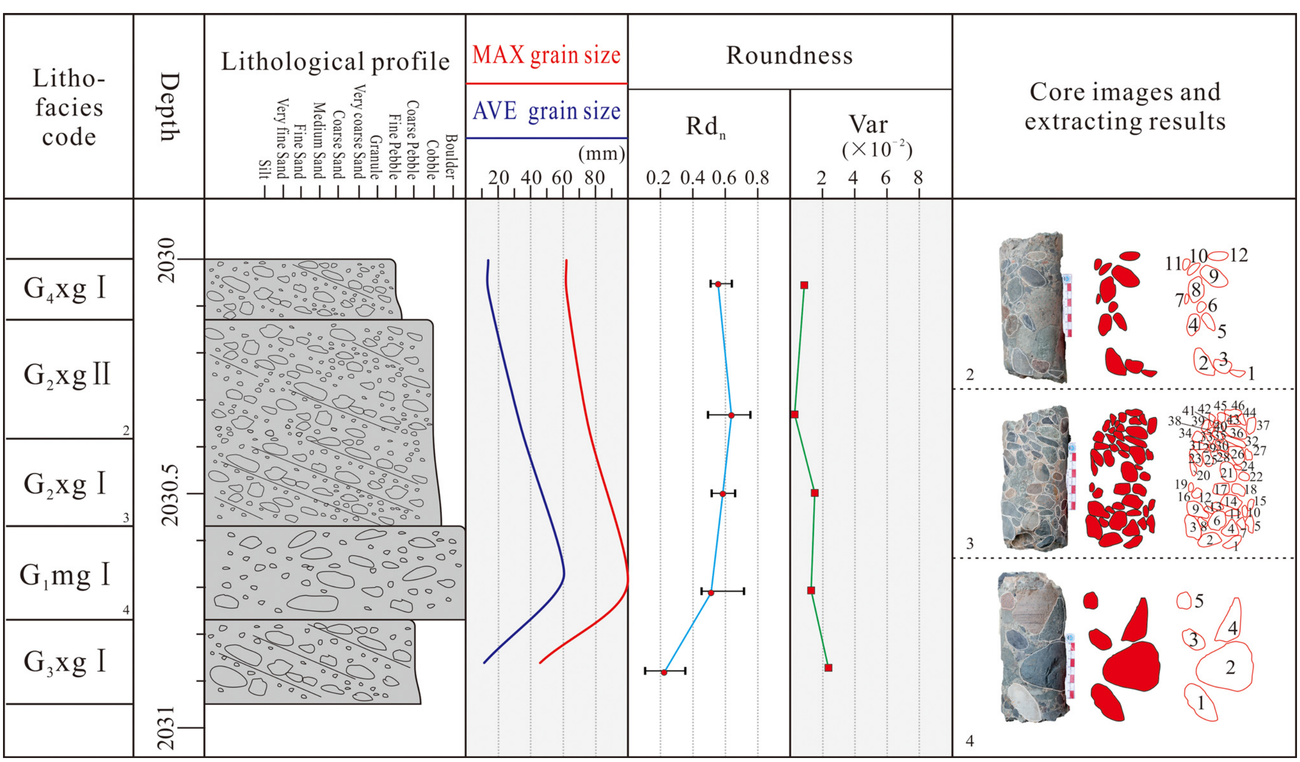

Figure 7: Roundness characteristics of typical braided channel deposit section in the Well X55.

as the hydrodynamic conditions at 2679.72 m changes during deposition. In conclusion, gravel roundness of submerged distributary channels microfacies is continuously getting better, with the roundness variance twice decreasing upward.

3.4 Submerged debris flow microfacies

Submerged debris flow Microfacies is defined as a subaqueous mass-transport deposits. Common lithofacies of submerged debris flow are G_5mrII, G_4mggII, G_4mgglll, which are gray-green, fine pebble, and granule conglomerates, mingled with coarse sandstones. In the upper layer, the granule layers sandwich between thin sandy layers. Total sequence manifests a set of finning-upward trend. The content of matrix is relatively higher than the submerged channels deposit, dominated by coarse and medium sands. The deposition is extremely poor sorted.

The typical section of submerged debris flow sedimentary microfacies in Mahu is 3311.15–3313.32 m in well MH 4. In this section, a total of 10 lithofacies were measured, with 184 pieces of gravels extracted (Table 2). Roundness at the lower part is mainly angular and sub-angular, while the upper part is sub-angular and sub-rounded. The range of roundness is 0.290–0.637. In addition, the mean Var of roundness is 0.033. The shape of its curve seems like a sine curve, which indicates that the distribution of roundness is sometimes concentrated and sometimes dispersed.

According to the trend of gravel roundness curves and its corresponding variance curves in vertical of typical submerged debris flow sedimentary profile (Figure 9), it is found that roundness in the lower part of the section is mostly angular and sub-angular. Better rounding is shown in the upper section, which is sub-angular and rounded and sub-angular. On the other hand, the roundness variance in the section is high, with rhythmic fluctuation upward. The extreme Var values appear twice, respectively, at the depth of 3312.81 and 3312.09 m, with the corresponding Rd_n value to be the minimum and angular. Combined with other sedimentary characteristics, the sedimentary structures of the lithofacies with large variance are mostly the massive structures, which means that high energy and rapid unloading sediments are accumulated with all kinds of roundness levels. Therefore, curves of gravel roundness and the corresponding variance in typical

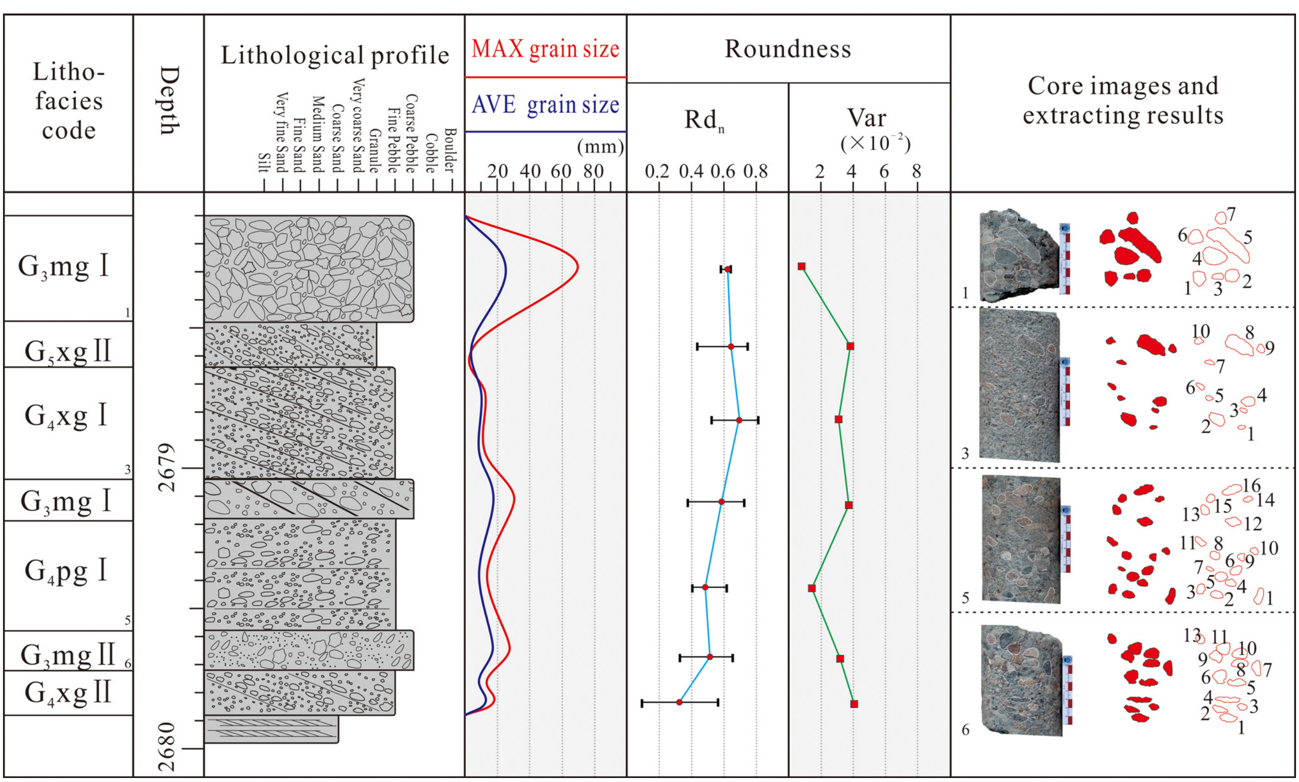

Figure 8: Roundness characteristics of typical submerged distributary channels deposit section in the Well FN15.

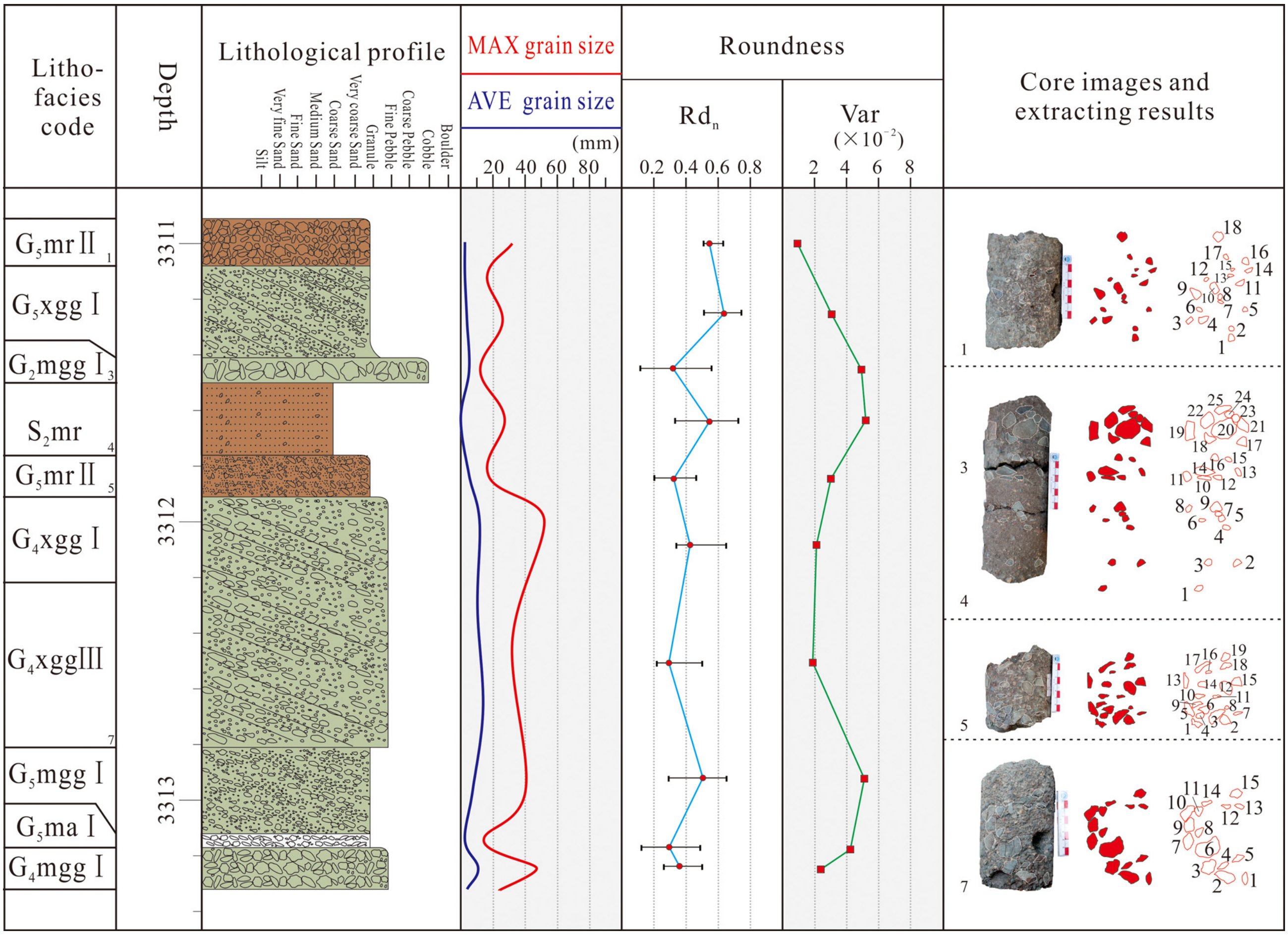

Figure 9: Roundness characteristics of typical submerged debris flow deposit section in the Well MH4.

submerged debris flow deposits are observed as obvious morphological fluctuations.

4 Discussion

Gravel roundness characteristics in Mahu fan delta deposits have different features in debris flow, submerged debris flow, braided channels, and submerged distributary channels. It appears that the sediments deposition process is of great significance in the particle roundness.

Further, there are many factors influencing the particles rounding degrees, such as the fluid properties during transportation and the extension scale of the sedimentary facies. In this part, the differences of gravel roundness of the sedimentary microfacies in Mahu are discussed. Also, we summarize the roundness characteristics in Table 3, including the numeric ranges and curves fluctuation features of roundness and its corresponding variance.

4.1 Gravel roundness of gravity flow deposition

Gravity flow is known as a kind of high-density fluid mixed with gravels, sands, mud, and water [2,17]. Disorderly thick bed with poorly sorted indicates mass transport and rapid deposits [52–54]. Two distinct microfacies are dominated by gravity flow in the study area: debris flow and submerged debris flow. Debris flow deposits are a part of fan delta plain, which are close to the source area [55]. However, the submerged debris flow deposits, as part of subaqueous deposits, are in the front of the fan delta and far away from the source area, caused by steep slope slides and collapses.

Comparing the typical core sections of debris flow deposits and submerged debris flow deposits in the study area, there are obvious morphological fluctuations in the gravel roundness and its variance curves (Table 2). The Rd_n curve of debris flow has a smaller fluctuation, but with a higher fluctuating frequency, ranging from sub-

Table 3: Comparison of gravel roundness and its variance curves results in typical core sections of sedimentary microfacies, T_1b, Mahu Area

Fluid property		Gravity flow deposition		Traction flow deposition	
Sedimentary microfacies		**Debris flow**	**Submerged debris flow**	**Braided channels**	**Submerged distributary channels**
Roundness curves (Rd_n)	Rd_n range	0.325–0.690	0.290–0.637	0.387–0.687	0.323–0.690
	AVE Rd_n	0.576	0.424	0.501	0.551
	Fluctuate amplitude	Low	Slightly higher	High	Slightly lower
	Fluctuate frequency	Slightly higher	High	Low	Slightly lower
	Trend upward	—	—	Up	Up
Roundness variance curves (Var)	Var range	0.005–0.092	0.009–0.052	0.009–0.024	0.007–0.040
	AVE Var	0.092	0.033	0.013	0.028
	Fluctuate amplitude	High	Slightly higher	Low	Slightly lower
	Fluctuate frequency	High	Slightly lower	Low	Slightly higher
	Trend upward	—	—	Down	Down

"—" means no obvious change.

angular to sub-angular and rounded. The Rd_n curve of submerged debris flow has a larger fluctuation range, from angular to sub-rounded. As for the roundness variance curves, variance of debris flow fluctuates greater than the variance of submerged debris flow. Numerically, the roundness value of debris flow is higher than that of submerged debris flow deposition, with an average value of 0.576 and 0.424, respectively. The Var values of debris flow are greater than the submerged debris flow, with an average of 0.092 and 0.033, respectively. In the vertical direction, roundness tends to be slightly worse upward in debris flow deposits. However, in the submerged debris flow, it runs the opposite.

Transport and deposition processes of gravel particles have an important impact on the roundness [2]. In gravity flow deposition, sediments collapse and break down at mountain or slopes [56,57]. At this time, the breccias suffer from short-distance transport. Angular clasts deposit with less wearing. Hence, the mixed composition of mud, sands, and gravels accumulate together with very poorly sorting. Coarse grains roll and drive the surrounding fine grains and coarse sands together. Some fine grains are blocked by coarse grains and did not break during transporting. That is why some rounded gravel particles appear at the proximal pass near the source, which explains that the roundness variance is large in the gravity flow deposits.

4.2 Gravel roundness of traction flow deposition

In terms of geographical position of channels, braided channels on the fan delta plain and submerged distributary channels on the fan delta front dominated the traction flow deposition in the study area. Braided channels deposits, as the main part of fan delta deposits, are characterized by mass flow, relatively adequate fluvial streams and stable runoff cycles. Furthermore, submerged distributary channels in the fan delta front are the extension of braided channels in the fan delta plain. The extension scale depends on the topographic slope.

The roundness curves of braided channels are observed as sharp fluctuation, ranging from angular to sub-rounded. Numerically, the roundness and its variance of submerged distributary channels are better than those of braided channels, with the average Rd_n value of 0.551 and 0.501, average Var value of 0.013 and 0.028, respectively. From the curves tendency in vertical direction of both fluvial deposits, the curves of gravel roundness tend to increase upward and the curves of its variance tend to decrease, formed gentle and smooth.

Previous studies indicate that particle roundness would tend to be better in the direction of sediment transport [58,59]. Roundness of submerged distributary channels in T_1b is indeed commonly observed to be better than the roundness of braided channels, although the shape of the curves and distribution of both microfacies are very similar.

4.3 Gravel roundness of gravity flow versus traction flow deposition

Quantitative results above demonstrate that gravel roundness of traction flow deposition is generally better than that of gravity flow deposition in T_1b of Mahu area. As for the curves fluctuating situation, the frequency of roundness and the variance curve of channels deposits are significantly lower than that of gravity flow deposits. In the vertical direction, roundness curves of channels deposition represent to be rounded, with the smaller variance upward, while the two curves in gravity flow deposits fluctuate frequently, with inconspicuous changes upward. The rounding mechanism in fluvial deposits is interpreted as continuous wearing and scouring in tractive flow. However, in gravity flow deposits, it is interpreted as the result of mass sediment transport and rapid deposition, which means the clastic particles are more easily to be broken. In addition, new components mixed in from other sources could also result in the change of roundness.

5 Conclusions

In this paper, we have investigated the gravel roundness characteristics of four kinds of typical sedimentary microfacies in the fan delta deposits of T_1b in Mahu Depression: debris flow, submerged debris flow, braided channels, and submerged distributary channels. Comparing the roundness, four microfacies from rounded to angular are braided channel deposits (Rd_n distribution range 0.379–0.603) > submerged distributary channel deposits (0.366–0.591) > debris flow deposits (0.333–0.405) > submerged debris flow deposits (0.256–0.391). The most concentrated roundness distributes in braided channels deposition, and roundness in debris flow is the most dispersed.

By observing the fluctuation of gravel roundness and the variance curves vertically of the typical core sections, it is considered that the gravel roundness curves of channels deposits appear to a large-ranging fluctuation, but with a small-ranging fluctuation in variance curves. As for the gravity flow deposits, the roundness curves of submerged debris flow fluctuate greatly, and so does the variance curves. Fluid property of the microfacies could be determined by the fluctuation of gravel roundness and its variance curves in the vertical direction. Combining with the numeric statistics of roundness and the corresponding variance, the specific sedimentary microfacies could be predicted. The quantitative roundness of the fan delta deposition in Mahu Depression provides a theoretical support for the conglomerates sedimentary facies interpretation.

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