DOWNSTREAM VARIATION IN PARTICLE SIZE, FORM, ROUNDNESS, AND LITHOLOGY : A CASE STUDY OF THE DOKI RIVER, SOUTHWEST JAPAN

Takeyuki UEKI

Abstract This study documents downstream variation in the maximum size, form, roundness, and lithology of particles along the mainstream of the Doki River, northeastern Shikoku Island, southwest Japan. In order to reconstruct the pattern of ancient streams with a typical geomorphological scale in Japan, that formed existing gravel deposits, geometrical indices complemetary to clast fabric data and representative of the particle population are proposed. For the paleocurrent interpretation, these should be relatively simple and less time-consuming to use. The maximum particle size progressively decreases downstream, while roundness increases. The proportion of clasts of a specified lithology varies downstream in an organized manner, especially far from the source area. In contrast, no particle form parameter shows significant downstream variation. These facts suggest that maximum particle size and roundness are useful parameters, and that lithological composition provides complementary data, while particle form is an unreliable factor for paleocurrent interpretation.

Key words : maximum diameter, roundness, lithology, form, Kagawa Prefecture

1. Introduction

This study aims to propose geometrical indices representative of particle populations, which are useful for reconstructing the patterns of ancient streams that formed existing gravel deposits. For this purpose, downstream variation in the maximum size, form, roundness, and lithology of particles along the mainstream of the Doki River, southwest Japan, were examined.

The uplift and denudation history of some ranges have been discussed, based on ancient stream patterns or change in facies within the conglomerates distributed along their foots (*e.g.* Hirabayashi 1970 ; McLaughlin and Nilsen 1982 ; Moriyama and Niwa 1985 ; Moriyama and Mitsuno 1989 ; Ueki and Mitusio 1998). In many of the previous studies, the paleocurrent directions at given localities have been obtained from clast fabric analyses. However, while these directions are merely the local downcurrent directions at these localities, analyses at numerous sites are needed to reconstruct the general downstream direction. Therefore, additional indices are required for paleocurrent interpretation, and these should be relatively simple and less time-consuming to use.

Since particle size, form, roundness, and lithology vary with the transportation distance, these data should also be available within a gravel deposit to supplement clast fabric data. and reconstruct the ancient stream pattern. Numerous studies have reported that particles become smaller and more rounded further downstream along the course of existing rivers. Particle form analyses are frequently undertaken to discriminate between depositional environments (*e.g.* Wentworth 1922a, b ; Cailleux 1947 ; Lenk-Chevitch 1959 ; Lüttig 1962 ; Sames 1966 ; King and Buckley 1968 ; Dobkins and Folk 1970 ; Stratten 1974 ; Dowdeswell *et al.* 1985 ; Benn and Ballantyne 1993). Flume experiments and field observations indicate that the downstream abundance of spherical and rod-shaped clasts results from shape sorting during transportation (Krumbein 1942a ; Hattingh and Illenberger 1995). So far as particle sphericity is concerned, however, decrease (Russell and Taylor 1937 ; Takei *et al.* 1987), increase (Krumbein 1941a ; Bradley 1970 ; Glover 1975 ; Moriyama and Masui 1981 ; Moriyama and Nakanishi 1991). and substantial invariability (Krumbein 1942b ; Plumley 1948 ; Lane and Carlson 1954 ; Blenk 1960 ; Bluck 1964 ; Dobkins and Folk 1970 ; Bradley *et al.* 1972 ; Goede 1975 ; Takahashi *et al.* 1987) have all been reported to occur further downstream. Unrug (1957) documented that particle sphericity increases downstream in the upper reach, whereas it decreases in the lower reach. Downstream variation in particle form depends upon the distinct size range and lithology of examined fragments (Allen 1948 ; Plumly 1948 ; Sneed and Folk 1958 ; Bluck 1965 ; Bradley 1970 ; Bradley *et al.* 1972 ; Goede 1975). These facts introduce doubt as to whether particle form is indicative of the general downstream direction. thus elaborate care should be taken in particle form studies.

Many extensive studies of particle size, form, roundness, and lithology have been undertaken along fluvioglacial streams or rivers more than several hundred kilometers long. Most alluvial and intermontane rivers in Japan are characterized by steep gradients and relatively short length of a few tens of kilometers or less. Variation in particle size, form, roundness, and lithology along such rivers is still unclear. Although this variation was reported in the 1950's and 60's, few studies collected these data along the entire reach of a river, and little attention has been called to particle form. It is, therefore, necessary to examine how particle size, form, roundness and lithology vary downstream along the entire reach of small rivers that are ubiquitous in Japan.

This study documents the downstream variation in particle size, form, roundness, and lithology along the Doki River, northeastern Shikoku Island, southwest Japan. Based on this variation, I attempt to suggest sedimentological factors for paleocurrent interpretation that are both reliable and convenient to investigate.

2. Study Area

The Doki River rises in the main ridge of the Asan Mountains and flows northwestward across central Kagawa Prefecture to enter the Seto Inland Sea. The river has a typical geomorphological scale of rivers in Japan. It is 21 km long and the catchment area is approximately 95 km^2, with a maximum relief of 1,060 m in elevation. The gradients of the lower, middle, upper, and uppermost reaches of the river are approximately 3 to 10, 17 to 22, 27 to 55, and more than 100 up to 400 per mill, respectively. Figure 1 illustrates the bedrock geology around the study area. The basin upstream from Locality 7 developed entirely in the

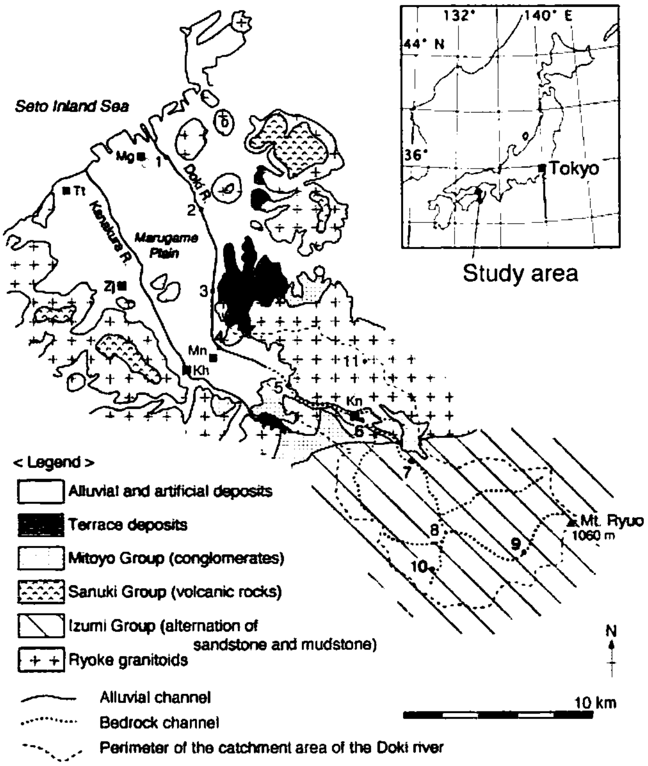


Fig. 1 Sampling sites and bedrock geology around the study area. The geologic map is simplified from Katto *et al.* (1977) and Ueki and Mitusio (1998). Numbers indicate sampling sites : 1. Kamibun, 2. Takayanagi, 3. Tarumi, 4. Shijo, 5. Sumisho, 6. Naiden, 7. Kawahigashi, 8. Myojin, 9. Kawaoku, 10. Shimobuke. Abbreviations are as follows : Kh. Kotohira, Kn. Kotonami, Mg. Marugame, Mn. Manno, Tt. Tadotsu. Zj. Zentsuji.

Cretaceous Izumi Group, which consists of alternating sandstone and mudstone intercalated with minor proportions of tuffaceous and gravel beds. Steep slopes with exceeding 400 m in relative height characterize this basin. In the middle reach, the river flows northwestward through hills 100 to 400 m in altitude, underlain by Cretaceous granitoids and Plio-Pleistocene Mitoyo Group. Badly weathered granitoids up to 10 m thick are intruded and capped by volcanic rocks (sanukitoid) of the Miocene Sanuki Group. The Mitoyo Group unconformably overlying the granitoids is an unconsolidated conglomerate 10 to 40 m thick. Pebble to cobble-sized clasts of crystalline-schists, as well as sandstone, mudstone, granitoids, and quartz, occur in this conglomerate (Ueki and Mitusio 1998). The Marugame Plain is composed of an alluvial fan deposit built up by the lower reach of the Doki River. The gradient of the graded-stream calculated in this reach is gentler than that in practice (Ichikawa and Ishikawa 1965). Moreover, the river has a gradient of 3 per mill at its mouth and the alluvial fan is not only dissected, but boulders from abandoned braided-streams are obvious on the surface (Oyama 1953 ; Ichikawa and Ishikawa 1965), suggesting that large amounts of sediments accumulated on the river floor under ungraded circumstances. Well-developed isolated mesa-shaped and conical hillocks underlain by igneous rocks occur in and around the plain.

3. Field Procedures and Laboratory Analyses

Sampling Sites

Particle size, form, roundness, and lithology were examined in eleven localities within the basin of the Doki River (Figs. 1 and 2). Localities 1-3 are located in the lower reach of the mainstream, where the longitudinal and transverse bars are well developed. Localities 4-6 are located in the middle reach ; longitudinal and transverse bars are found at Locality 4, while bedrocks of granitoids partly overlain by thin gravelly beds occur at Localities 5 and 6. Localities 7-9 are located in the upper reach, where steeply incised valleys result in bedrock channels. In this reach, the bedforms are characterized by transverse lunate bars or small-scale riffle bars, which Martini (1977) described as gravelly flood deposits. At each locality, a position on the bar adjacent to the largest particle on the surface, at which the bedform was not artificially disturbed, was chosen for sampling. Localities 10 and 11 on the mountain slope were also examined ; here colluvial deposits underlain by sandstone and granite bedrock, respectively, occur in road-cuts.

Maximum Particle Size

Since it is difficult to dig out huge boulders from the bed and therefore almost impossible to measure all three dimensions of these clasts in the field, the apparent longest and intermediate axes of the ten largest exposed particles in a 10 × 10 m area were measured with a folding ruler. The average intermediate diameter (Ouchi 1979) and maximum-projection-plane diameter (Moriyama and Niwa 1985) of the specified number of clasts were used as the maximum particle diameters. Since the settling velocity of a particle is related to the area of the maximum-projection-plane (Krumbein 1942b ; Sneed and Folk

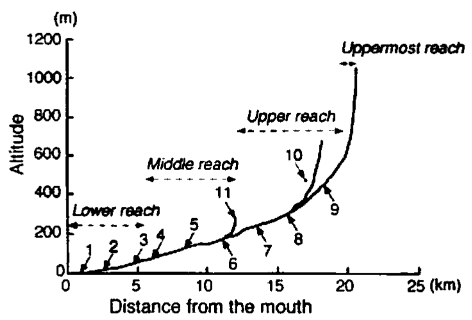


Fig. 2 Longitudinal profile of the entire Doki River. The ordinate scale is five times exaggerated to the abscissa. The numbers correspond to the sampling sites illustrated in Fig. 1.

1958). the maximum-projection-plane diameter of each particle was determined in this study as the geometric mean of two dimensions in the plane. Thereafter, the average diameter of the ten largest particles frequently standardized in clast size studies (Eckis 1928 ; Pelletier 1958 : Bluck 1964, 1965 : Steel *et al.* 1977 : Moriyama and Niwa 1985 : Moriyama and Mitsuno 1989 : Ueki and Mitusio 1998) was examined, and compared with diameters of the largest and the fifth largest particles. The diameter of the fifth largest clast was proposed as maximum particle size (Nogami. personal communication). It is complicated, time consuming. and laborious to estimate the median diameter ($M_d\phi$), though it is familiar index describing a sediment. Therefore $M_d\phi$ is considered to be inadequate for examinations at numerous sites. Although the average volume of a specified number of the largest clasts has been defined as maximum particle size (Mino 1950 : Nakayama 1952 : Takakuwa and Deishi 1954), determining this factor requires patience and plenty of time. In this study, the maximum diameter of the particles was used instead, because it is relatively simple and much quicker to determine. Even though the maximum diameter of the particles can be estimated as the order of 1 centimeter. the diameter was empirically sufficient for the paleocurrent interpretation in Japan (Moriyama and Niwa 1985 : Moriyama and Mitsuno 1989 : Ueki and Mitusio 1998). The most likely explanation of this availability is that significant downstream decrease of the maximum particle diameter along the small scaled rivers results from its exponential downstream decrease (Krumbein 1937 ; Mino 1950 : Bluck 1964 : Kodama 1994).

Particle Form

For the form analyses. a total of 270 or 150 particles, including those of sandstone and granitoids. were examined at each locality. Sets of 100 and 50 clasts of sandstone. with a longest dimension ranging from 32 to 128 mm (-5 to -7 on the phi-scale). and a relatively more comprehensive range of pebble to cobble size grades. were randomly collected from the bar deposits at all localities. Additional sets of 100 and 20 clasts of granitoids in the same size ranges were also collected at random at Localities 1 to 6. In the laboratory. each clast was measured in three orthogonal dimensions with a vernier caliper. These were regarded as the length. breadth, and thickness of the particle. Numerous indices determined from the three axes have been proposed as representative of general particle form. These indices conceptualize the flatness. sphericity, elongation (oblate-prolateness). and relative uniformity of all three axes and dominant particle form. This study did not consider several indices, including dissymmetry (Cailleux 1945). which requires additional axial information. or two-dimensional sphericity determined from the visual charts illustrated in Rittenhouse (1943), Krumbein and Sloss (1951). and Powers (1982). Twenty-five form parameters were calculated from these axial lengths in three specified size grades (-5 to -5.5. -5.5 to -6. and -6 to -6.5 phi-scale). The formulae for these parameters are summarized in the Appendix 1. Each particle was classified as rod-shaped. bladed. discoid. or spherical by plotting the axial ratios on the form diagram (Zingg 1935), and the proportions of all four form classes were determined. The form ratio was also computed from the numbers of clasts that fell within each class in the triangular form diagram (Sneed and Folk 1958). These form diagrams and distinct subdivided form classes are shown in Appendix 2.

Particle Roundness

The visual comparison chart developed by Krumbein (1941b) was used to determine two-dimensional particle roundness, because it is simple and has the most distinct subdivisions. Various indices representative of particle roundness have also been recommended. Since tedious, complicated, and time-consuming procedures are required to determine the Wadell roundness of each clast exactly (Wadell 1932), pebble image sets of predetermined roundness have been prepared for the convenience of determination (Trowbridge and Mortimore, 1925 ; Russell and Taylor 1937 ; Krumbein 1941b ; Pettijohn 1949, 1957 ; Krumbein and Sloss 1951 ; Powers 1953 ; Schneiderhöhn 1954 ; Eißele 1957a, b ; Reichelt 1961). Visual comparison method using the Krumbein chart is sufficient for this study, because my purpose was to identify particle parameters that are useful for reconstructing the pattern of ancient streams that formed gravel deposits.

Particle Lithology

The composition of each lithology was determined by the visual comparison method from more than 300 randomly-sampled particles with a longest axis larger than 1 cm. Each particle was classified into five rock types : sandstone, mudstone, tuffstone, granitoids, or quartz.

5. Results

Variation in Maximum Particle Diameter

Variation in the maximum particle diameter as a function of the distance from the mouth is shown in Fig. 3. Although exceptionally large clasts of sandstone, mudstone, and granitoids contribute to the abrupt increases in maximum particle diameter at Localities 8, 7 and 5, respectively, the diameters of all lithologies generally decrease downstream. The maximum particle diameter of sandstone almost follows a linear relationship with the

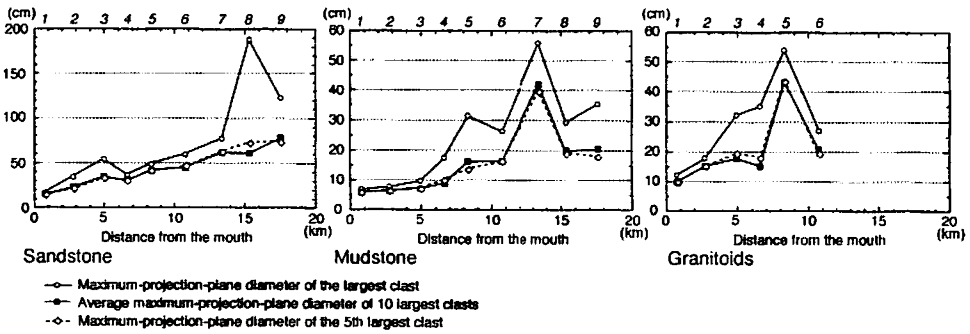


Fig. 3 Variation in the maximum diameter of particles as a function of distance from the mouth. Italic numbers on the upper abscissa correspond to the sampling sites illustrated in Fig. 1. Maximum particle size of each lithology shows general trend of downstream variation, though the abrupt local increase at a certain site is observed.

transportation distance in the whole reach. The trend of maximum particle diameters of both mudstone and granitoids also decrease downstream in the middle to lower reaches, although the results are more scattered. This variation does not follow the exponential relationship generally identified in many previous studies (Krumbein 1937 ; Mino 1950 ; Bluck 1964 ; Kodama 1994). The variation in the average maximum-projection-diameter of the ten largest clasts is consistent for each rock type with the maximum-projection-diameter of the fifth largest clast.

Variation in Particle Roundness

The particle roundness of both sandstone and granitoids generally shows increasing variation downstream (Fig. 4). Both clasts in the colluvial deposits of sandstone at Locality 10 and granite at Locality 11 have an extremely low roundness of less than 0.1. These are succeeded by subangular clasts after transportation of less than a few kilometers. For sandstone clasts, the roundness in the pebble to cobble size grade increases curvi-linearly downstream. From the perspective of roundness variation in all the specified size ranges, the entire Doki River can be divided into three sections. Along the upstream and downstream sections (between Localities 1 and 4, and Localities 7 and 9, respectively), roundness increases downstream, whereas along the midstream section (between Localities 4 and 7), roundness remains constant and do not change with the distance transported. For clasts of granitoids, although local downstream decreases in roundness are discerned at Localities 1 and 3, a general downstream increase is evident. The roundness of both sandstone and granitoids in all specified size grades are related to the transportation distance. However, downstream variation in roundness here does not follow the exponential relationship (Wentworth 1919, 1922b : Krumbein 1940 : Plumly 1948), but the linear relationship identified in previous studies in Japan (Nakayama 1954, 1960, 1963).

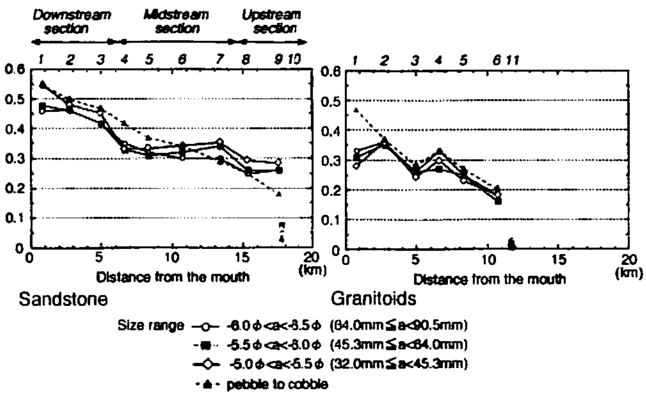


Fig. 4 Variation in particle roundness as a function of distance from the mouth. Italic numbers are the same as Fig. 3. Particle roundness of both sandstone and granitoids in all specified size grades are related to the transportation distance. From the variation in roundness of sandstone clasts, the entire Doki River is divided into three sections.

Variation in Particle Lithology

Variation in lithology as a function of the distance from the mouth is illustrated in Fig. 5. The proportions of clasts of sandstone and mudstone are almost constant in the upper reach, where the bedrock geology are the same to these rocks. In the middle to lower reach, along which igneous bedrocks develop, the proportion of sandstone clasts increases exponentially downstream. To the contrary, the proportions of clasts of mudstone and granitoids both decrease exponentially downstream. The percentage of tuffstone clasts is constantly less than two in the entire reach.

Variation in Particle Form

Figures 6 and 7 illustrate the variation in the generalized particle form of sandstone and granitoids, respectively, with the distance from the mouth. The variation in the proportion of clasts within each Zingg form class and form ratio is shown in Fig. 8. In contrast to the variation in maximum particle diameter, roundness, and lithological composition, no form parameter shown in these Figures exhibits unequivocal systematic downstream variation, because of invariability or a large range of dispersion from locality to locality. Several parameters of sandstone clasts in certain size grades show obscure regarding downstream variation. Almost none of the form parameter relationships differentiate the rock type, whereas within the same lithology, a significant difference emerges in respect to the examined size grade. Variation in the form parameters of sandstone clasts is more extensively influenced by the examined size grade than in granitoids. These facts do not indicate the independence of particle form on their size (Carroll 1951), but suggest the distinct control of the examined size grade on particle form (Plumly 1948 ; Sneed and Folk 1958). Although several parameters (*e.g.* Nakayama flatness) are independent of the examined size grade, unfortunately there is no apparent downstream trend in this variation. Figure 8 illustrates that no distinct form becomes predominant downstream in each lithology. This does not agree with the expectation that discoid clasts may be looked upon as a population

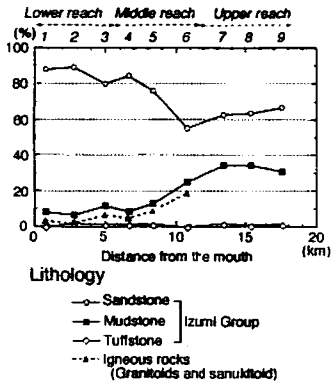


Fig. 5 Variation in lithology as a function of distance from the mouth. Italic numbers are the same as Fig. 3. In the upper reach, proportions of all lithologies remain conatant. To the contrary, proportion of sandstone clasts in the lower to middle reach increases downstream, whereas those of mudstone and granitic clasts decrease.

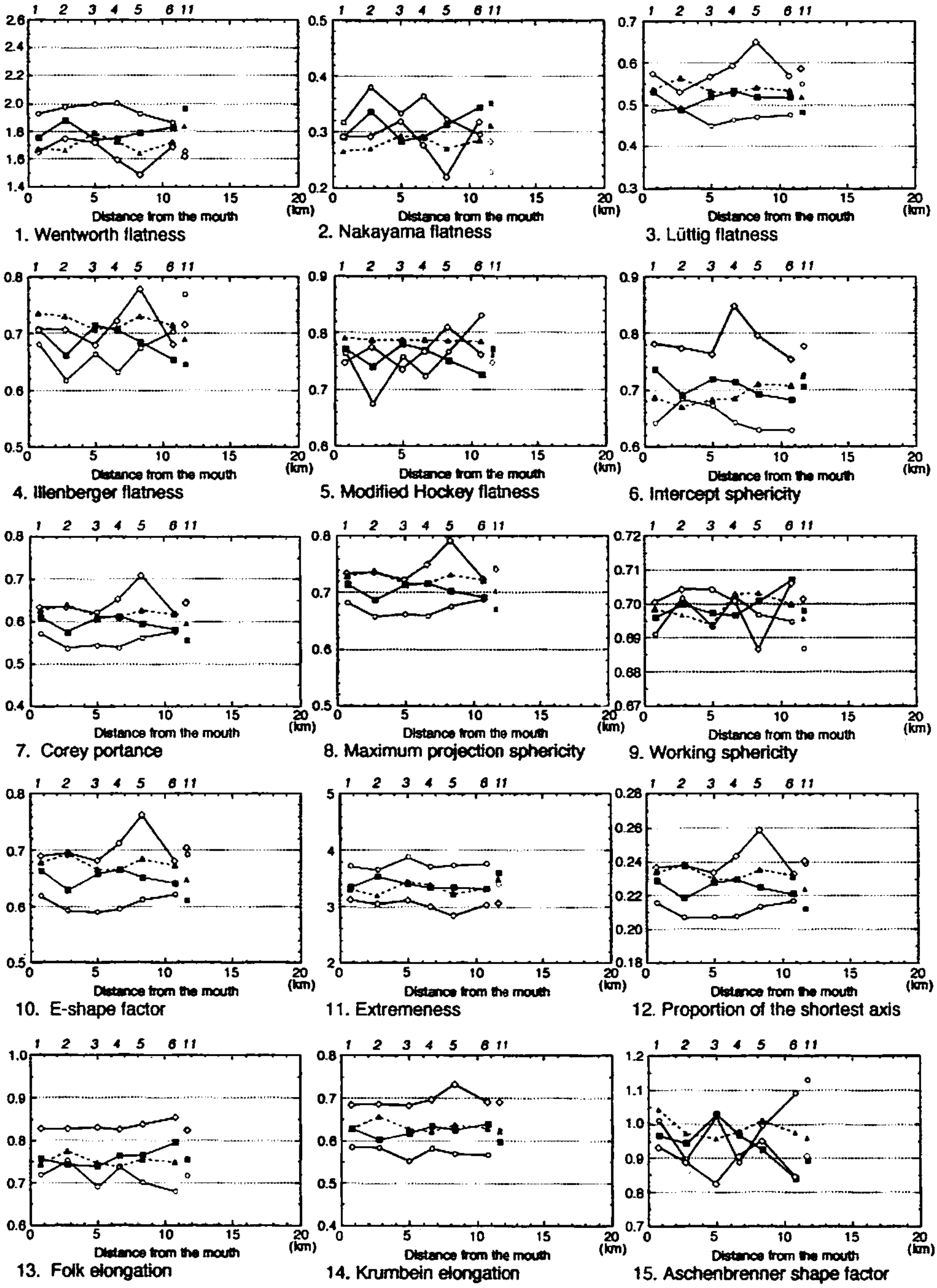
which systematically varies in abundance downstream (Bluck 1965). Although a slight downstream increase in the form ratio of sandstone clasts in all three size grades is recognized. no downstream variation is apparent in the granitoids clasts. The proportion of clasts in each form class is also affected by the examined size grade, in the same manner of the variation in form parameters.

6. Discussion and Conclusions

Maximum particle size and roundness are reliable indices for reconstructing the pattern of ancient streams forming gravel deposits such as those in the typical small rivers found in Japan. The particle lithology complements these indices, whereas particle form parameters are not helpful for this purpose.

Maximum particle size generally decreases downstream. while roundness increases. Hence, these indices are regarded as a function of the transportation distance. This study documented the downstream decrease in maximum particle size by using relatively quick and simple methods. The observed downstream decrease in maximum particle size is in accord with previous studies of the distribution of median diameter (Yatsu and Otsuka 1948 ; Yatsu 1951 ; Inokuchi 1954 ; Kodama 1994), and average volume of the largest clasts of the given numbers (Mino 1950 ; Nakayama 1952 ; Takakuwa and Deishi 1954). It seems that maximum particle size is sufficient index to show a general downstream trend, and is more convenient one for paleocurrent interpretation than median diameter or maximum particle volume. The observed downstream increase of roundness also agrees with previous studies (Nakayama 1954, 1960, 1963 ; Nakayama and Miura 1964). These conclusions provide fundamental assurance that the pattern of ancient streams forming gravel deposits can be reconstructed from the variation in maximum particle diameter or particle roundness. as has been applied in several studies of ancient conglomerates (Ouchi 1979 ; Moriyama and Niwa 1985 ; Moriyama and Mitsuno 1989 ; Ueki and Mitusio 1998). An abrupt local increase in the maximum diameter of the largest clast occurs at several localities, probably as a result of the tributary effect suggested by Bluck (1964) and Shimazu (1990) or collapse of the bedrock-wall immediately upstream from these localities. On the other hand, the average maximum diameter of the ten largest clasts and the diameter of the fifth largest clast show a generalized downstream decrease. The diameter of the fifth largest clast is recommended as an appropriate parameter to quantify systematic downstream variation, because of the most rapid and simplest examination. The roundness of both sandstone and granitoids clasts in all specified size grades and the pebble to cobble size range decreased downstream. Therefore, in roundness studies, it is sufficient to collect particles in a relatively wide range of pebble to cobble sizes, rather than from specific phi-scale intervals, from a viewpoint of efficiency.

The proportions of clasts of sandstone and mudstone are almost constant in the upper reach, where the bedrock geology is the same to these rocks. The almost invariable proportion of relatively less durable mudstone clasts implies that large amounts of debris of both sandstone and mudstone are supplied to the mainstream from the tributaries along this reach. In the middle to lower reaches, where igneous bedrocks develop, the proportion of sandstone clasts increases downstream, while the proportions of both mudstone and



Continued to the next page

Fig. 6.

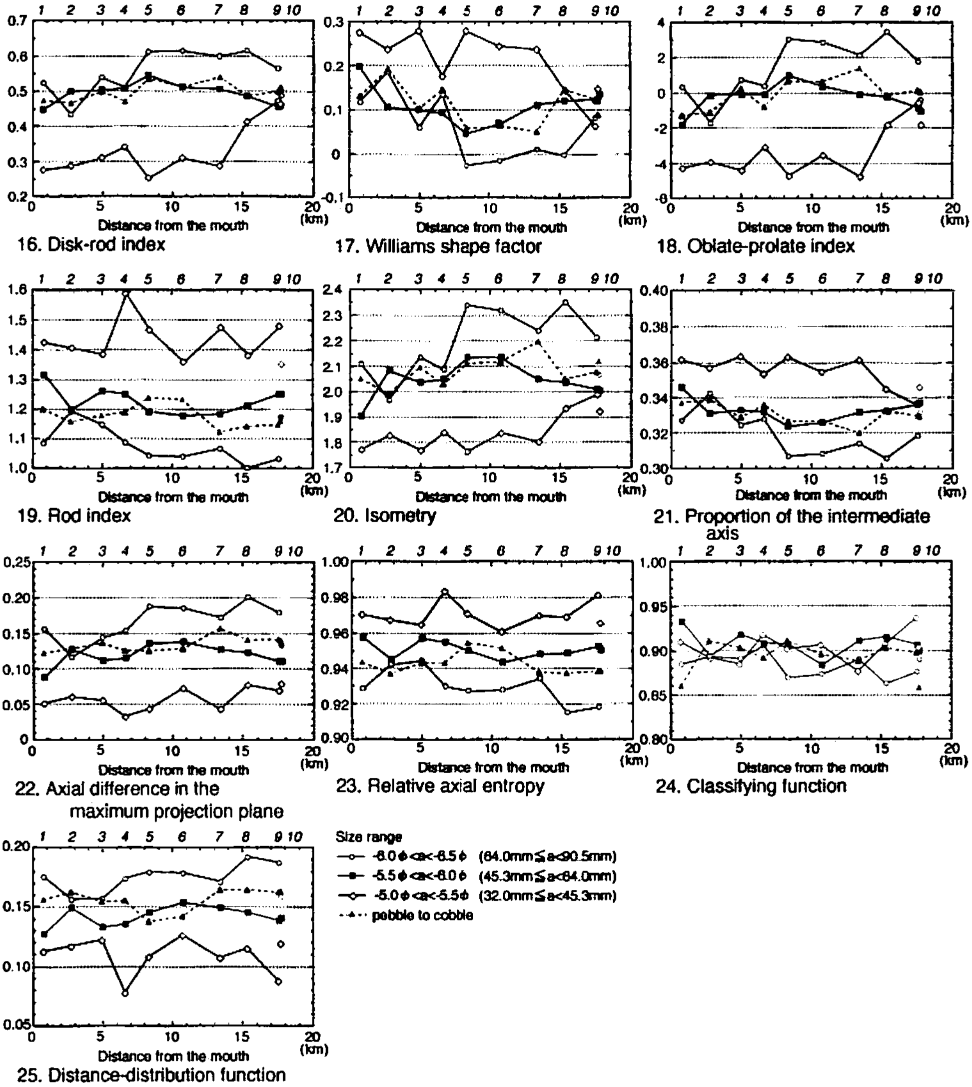
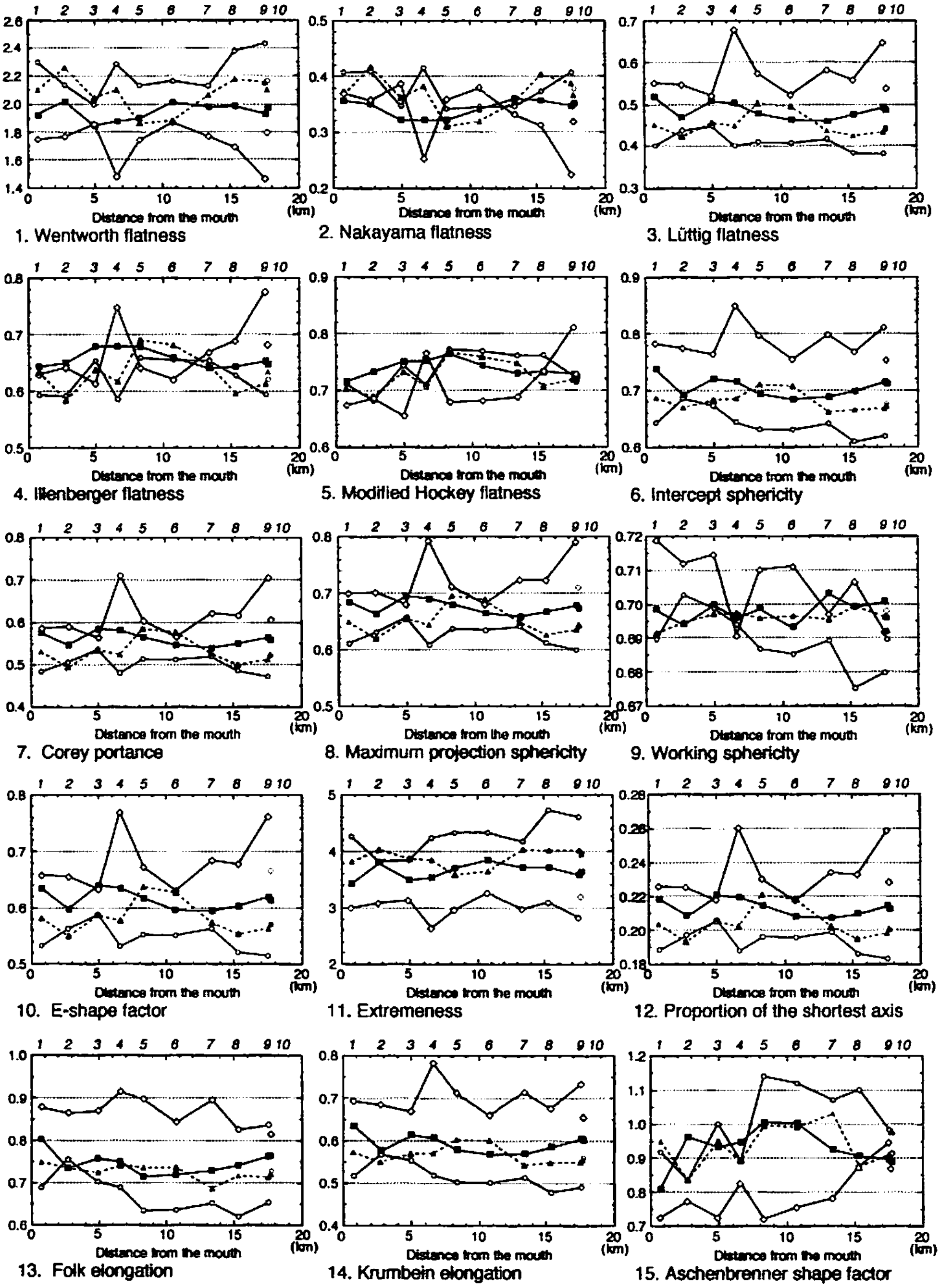


Fig. 6 Variation in form parameters of sandstone particles as a function of distance from the mouth. Italic numbers are the same as Fig. 3. The formulae of these form paramaters are shown in Appendix 1 with the same number of each figure. These form parameters have a distinct range and dispersion. hence it is only meaningful to discuss the variation in each parameters against the transportation distance. No form parameters of sandstone particles in all specific size grades exhibits a general trend of downstream variation. Almost all of form parameters have a large range of dispersion from locality to locality and dependence on the examined grain size grade.



Continued to the next page

Fig. 7.

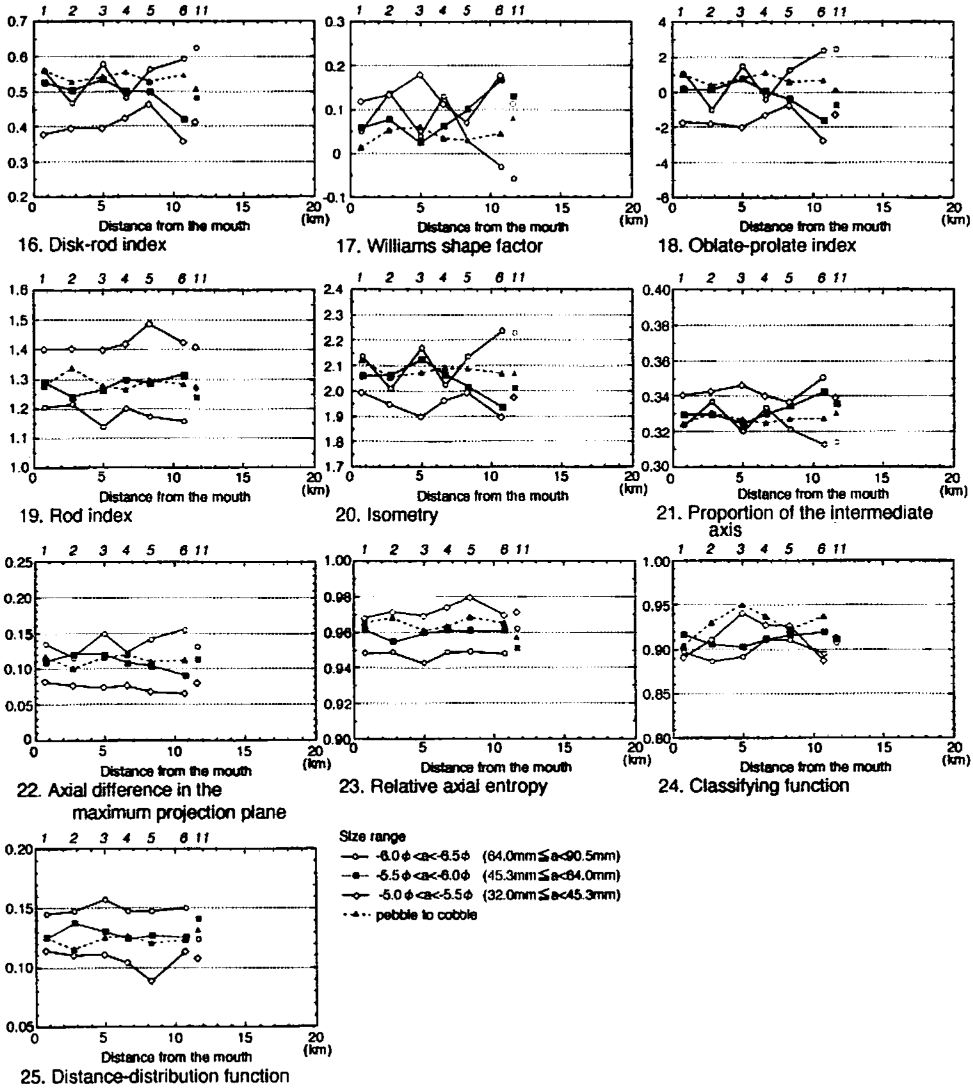


Fig. 7 Variation in form parameters of granitic particles as a function of distance from the mouth. Italic numbers are the same as Fig. 3. The formulae of these form paramaters are the same as Fig. 6. As well as the form parameters of sandstone clasts, there is no significant relationships in all specific size grades between each parameter and the transportation distance. A large range of dispersion from locality to locality and dependence on the examined grain size grade are also discernible.

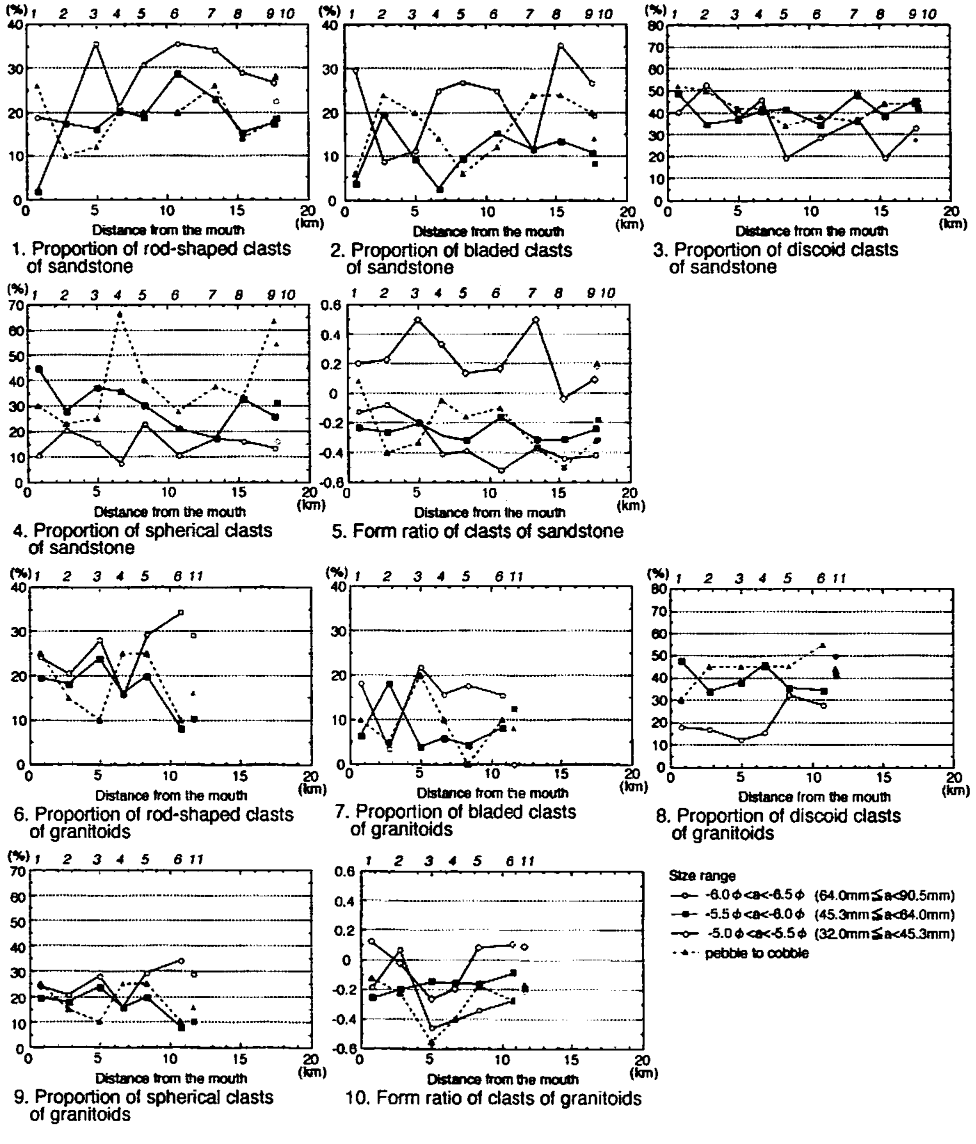


Fig. 8 Variation in the proportions of clasts plotted in each Zingg form class and form ratios as a function of distance from the mouth. Zingg form diagram and its subdivision into each form class are illustrated in Appendix 2. The formula of the form ratio is shown in Appendix 1. The proportion of each clast form in the range -5 to -5.5 on the phi-scale is not shown, because there were too few measurements. Italic numbers are the same as Fig. 3. No distinct form of both sandstone and granitic particles becomes predominant downstream in all specified size grades. Form ratio of both lithologies follows a random variation with the transportation distance. All of these factors representing of particle form have a large range of dispersion from locality to locality and depend on the examined grain size grade.

granitoid clasts decrease. These results suggest that the tributaries supply little granitoid debris to the mainstream in the lower reach, probably since the source area is confined within lower relief hillocks. This may also be due to the fact that granitoid debris is smaller, averaging 1 to -2 on the phi-scale as compared with -4.5 to -6.1 for sandstone (Ichikawa 1958). Clasts of granitoids are also abraded much more rapidly than those of sandstone (Takakuwa and Deishi 1954 ; Nakayama and Miura 1964 ; Hirabayashi 1966). Although there is no supply of sandstone debris to the mainstream in the lower reach, the proportion of sandstone clasts increases downstream, because of its hardness and low influx of granitoid debris. Consequently, the relatively less durable clasts of mudstone and granitoids become scarce downstream. It is concluded that the proportions of clasts of sandstone and mudstone are functions of the distance from their source area. Although the proportion of granitoid clasts is expected to increase downstream with the distance from the edge of its source area, the proportion actually shows the opposite relationship due to the reasons discussed above.

In contrast to the particle size, roundness, and lithology, a few form parameters of each rock type show some downstream variation in one or two specified size ranges. There is no systematic downstream variation in a single form parameter in all specified size grades. The variation in most of the form parameters is influenced by the examined size grade and changes extensively from locality to locality. Moreover, no distinct particle form of any lithology is significantly predominant downstream. Unlike these results, weakly systematic variation in particle form factors have been found in relatively large rivers in Japan, but this is restricted to within given sections (Moriyama and Masui 1981 ; Takei *et al.* 1987 ; Moriyama and Mitsuno 1989). The observed downstream variation in form parameters in this study agrees with the results of Takahashi *et al.* (1987), who examined particle form along a river of the same scale as the Doki River. Therefore, it is concluded that along small-scale rivers, particle form parameters and the frequency of each clast form class essentially vary randomly downstream, and most of these factors are dependent on the examined size grade. No form parameter shows a general downstream decrease or increase along rivers for all spatial scales.

Lithology has no effect on the particle form. The flattened form is regarded as the principal one in population of sandstone clasts, from a viewpoint of its textual anisotropy. Equidimensional form is looked upon the principal ones in population of granitic clasts because of its textual homogeneity. Against this consideration, clasts of sandstone and granitoids have no predominant form, and there is consequently no appreciable difference in the sphericity (*e.g.* working sphericity shown in Figs. 6-9 and 7-9) and elongation (*e.g.* Williams shape factor shown in Figs. 6-17 and 7-17) of the two rock types. This may be due to the fact that sedimentary rocks are not fractured along the bedding planes in a reproducible manner (Drake 1970).

In summary, because paleocurrent direction from clast fabric analysis at a given site does not show general trend of downstream direction but indicate merely a local downcurrent one, additional indices are required for paleocurrent interpretation, and these should be relatively simple and less time-consuming to use. Maximum particle size and roundness vary systematically downstream along the entire reach of the Doki River. Therefore, these parameters are appropriate for reconstructing the pattern of ancient streams with a few tens of kilometers long, which formed gravel deposits. The maximum-projection-plane diameter of the fifth largest clast is recommended as representative of maximum particle diameter for this purpose. The proportion of a specified rock type increases or decreases downstream far from its source area, hence lithological composition is regarded as additional information to supplement maximum particle size and roundness. To the contrary, particle form is considered to be an unreliable factor for paleocurrent interpretation, because of its unsystematic downstream variation, a large range of dispersion from locality to locality, and dependence on the examined grain size grade.

Acknowledgments

I would like to thank Professor Haruo Yamazaki, Dr. Shuji Yamada and Dr. Takashi Kumamoto of Tokyo Metropolitan University who made helpful comments on an early version of the manuscript. Special thanks are provided to Mr. Ken-ichi Kondo and his family of Saita Town, Kagawa Prefecture, who afforded an accommodation for my field work.

References

Allen, P. 1948. Wealden petrology : the top Ashdown pebble bed and the top Ashdown Sandstone. *Quat. Jour. Geol. Soc. London* **104**: 257-321.

Aschenbrenner, B. C. 1956. A new method of expressing particle sphericity. *Jour. Sed. Petrol.* **26**: 15-31.

Benn, D. I. and Ballantyne, C. K 1993. The description and representation of particle shape. *Earth Surface Processes and Landforms* **18**: 665-672.

Blenk, M. 1960. Ein Beitrag zur morphometrischen Schotteranalyse. *Zeit. Geomorphol., N. F., Bd.* **4**: 202-242.

Bluck, B. J. 1964. Sedimentation of an alluvial fan in southern Nevada. *Jour. Sed. Petrol.* **34**: 395-400.

Bluck, B. J. 1965. The sedimentary history of some Triassic conglomerates in the Vale of Glamorgen, south Wales. *Sedimentology* **4**: 225-245.

Bradley, W. C. 1970. Effect of weathering on abrasion of granitic gravel, Colorado River (Texas). *Geol. Soc. Am. Bull.* **81**: 61-80.

Bradley, W. C., Fahnestock, R. K. and Rowekamp, E. T. 1972. Coarse sediment transport by flood flows of Knik River, Alaska. *Geol. Soc. Am. Bull.* **83**: 1261-1284.

Cailleux, A. 1945. Distinction des galets marins et fluviatiles. *Bull. Soc. Géol. Fr., Ser.* **515**: 375-404.

Cailleux, A. 1947. L'indice d'émousse : Définition et première application. *Comptes Rend. Somm. Géol. Fr.* **13**: 250-252.

Carroll, D. 1951. Pebbles from a pothole : a study in shape and roundness. *Jour. Sed. Petrol.* **25**: 271-301.

Corey, A. T. 1949. *Influence of shape on fall velocity of sand grains.* Unpublished M. S. thesis, Colorado A & M College, 102p. Cited in Flemming (1965), and Dobkins and Folk (1970).

Dobkins, J. E. and Folk, R. L. 1970. Shape development on Tahiti-Nui. *Jour. Sed. Petrol.* **40**:

1167-1203.
Dowdeswell, J. A., Hambrey, M. J. and Wu, R. 1985. A comparison of clast fabric and shape in late Precambrian and modern glacigenic sediments. *Jour. Sed. Petrol.* **55**: 691-704.
Drake, L. D. 1970. Rock texture : an important factor for clast shape studies. *Jour. Sed. Petrol.* **40**: 1356-1361.
Eckis, R. 1928. Alluvial fans in the Cucamonga District, southern California. *Jour. Geol.* **36**: 224-247.
Eißele, K. 1957a. Kritische Betrachtungen einer Methode zur Bestimmung des Rundungsgrades von Sandkörnern. *Neues Jahrb. Geol. Paläontol.* **99**: 410-419.
Eißele, K. 1957b. Sedimentpetrographische Untersuchungen am Buntsandstein des Nordschwarzwaldes. *Jahrb. Geol. Landesamtes* **2**: 69-117.
Flemming, N. C. 1965. Form and function of sedimentary particles. *Jour. Sed. Petrol.* **35**: 381-390.
Folk, R. L. 1955. Student operator error in determination of roundness, sphericity, and grain size. *Jour. Sed. Petrol.* **25**: 297-301.
Forgotson, J. M. 1960. Review and classification of quantitative mapping techniques. *Bull. Am. Associ. Petrol. Geol.* **44**: 83-100.
Glover, B. K. 1975. A morphometric analysis of terrace gravels in Santa Ynez Basin, Santa Barbara Country, California. *Sediment. Geol.* **13**: 109-124.
Goede, A. 1975. Downstream changes in shape in the pebble morphometry of the Tambo River, eastern Victoria. *Jour. Sed. Petrol.* **45**: 704-718.
Goguel, J. 1953. A propos de la mésure des galets et de la définition des indices. *Rev. Géomorphol. Dyn.* **4**: 115-118.
Graham, J. 1988. Collection and analysis of field data. In *Techniques in Sedimentology*, ed. Tucker, M., 5-62, Oxford : Blackwell Science.
Hattingh, J. and Illenberger, W. K. 1995. Shape sorting of flood-transported synthetic clasts in a gravel bed river. *Sediment. Geol.* **96**: 181-190.
Hirabayashi, T. 1966. Provenance of the Tertiary conglomerates east of the Matsumoto Basin, Nagano Prefecture. *Jour. Geol. Soc. Japan* **72**: 191-203. **
Hirabayashi, T. 1970. Neogene conglomerates and Cenozoic geohistory of the northern Fossa Magna in central Japan. *Jour. Associ. Geol. Collab. Japan* **24**: 79-92, 115-128.
Hockey, B. 1970. An improved co-ordinate system for particle shape representation. *Jour. Sed. Petrol.* **40**: 1054-1057.
Hofmann, H. J. 1994. Grain-shape indices and isometric graphs. *Jour. Sed. Res.* **A64**: 916-920.
Ichikawa, M. 1958. On the debris supply from mountain slopes and its relation to river bed deposition. *Sci. Rep. Tokyo Univ. Edu., Sec. C* **6**: 1-29.
Ichikawa, M. and Ishikawa, Y. 1965. Fluvial deposits and the grade of river floor of the Doki, Japan. *Sci. Rep. Tokyo Univ. Edu., Sec. C* **9**: 1-16.
Illenberger, W. K. 1991. Pebble shape (and size!). *Jour. Sed. Petrol.* **61**: 756-767.
Illenberger, W. K. 1992. Pebble shape (and size!) — Reply. *Jour. Sed. Petrol.* **62**: 1151-1155.
Illenberger, W. K. and Reddering, J. S. V. 1993. An evaluation of shape indices as paleoenvironmental indicators using quartzite and metavolcanic clasts in Upper Cretaceous to Paleogene beach, river and submarine fan conglomerates: Discussion. *Sedimentology*, **40**: 1019-1021.

Inokuchi, M. 1954. Problems associated with the Makinohara Gravel Beds. *Geogr. Rev. Japan* **27**: 184-192. **

Janke. N. C. 1966. Effect of shape upon the settling velocity of regular convex geometric particles. *Jour. Sed. Petrol.* **36**: 370-376.

Katto, J.. Suyari. K.. Kashima. N., Hashimoto, I.. Hada, S., Mitsui, S. and Akojima, I. 1977. *Kochi eirinkyoku kan-nai hyoso chishitu zu (Surface geologic map within the jurisdiction of the Forestry Bureau of Kochi).* Scale 1 : 200 000. Kochi : Forestry Bureau of Kochi. *

King. C. A. M. and Buckley. J. T. 1968. The analysis of stone size and shape in arctic environments. *Jour. Sed. Petrol.* **38**: 200-214.

Kodama. Y. 1994. Downstream changes in the lithology and grain size of fluvial gravels. the Watarase River, Japan : evidence of the role of abrasion in downstream fining. *Jour. Sed. Res.* **A64**: 68-75.

Krumbein. W. C.. 1937. Sediments and exponential curves. *Jour. Geol.* **55**: 577-601.

Krumbein, W. C. 1939. Application of photo-electric cell to the measurement of pebble axes for orientation analysis. *Jour. Sed. Petrol.* **9**: 122-130.

Krumbein, W. C. 1940. Flood gravel of San Gabriel Canyon. California. *Bull. Geol. Soc. Am.* **51**: 639-676.

Krumbein, W. C. 1941a. The effect of abrasion on the size. shape and roundness of rock fragments. *Jour. Geol.* **49**: 482-520.

Krumbein, W. C. 1941b. Measurement and geological significance of shape and roundness of sedimentary particles. *Jour. Sed. Petrol.* **11**: 64-72.

Krumbein, W. C. 1942a. Settling-velocity and flume-behaviour of non-spherical particles. *Trans. Am. Geophys. Un.* **23**: 621-632.

Krumbein. W. C. 1942b. Flood deposits of Arroyo Seco, Los Angeles Country. California. *Bull. Geol. Soc. Am.* **53**: 1355-1402.

Krumbein. W. C. 1955. Composite end members in fabric mapping. *Jour. Sed. Petrol.* **25**: 115-122.

Krumbein, W. C. and Sloss. L. L. 1951. *Stratigraphy and Sedimentation.* San Francisco : Freeman.

Lane, E. W. and Carlson, E. J. 1954. Some observations on the effect of particle shape on the movement of coarse sediments. *Trans. Am. Geophys. Un.* **35**: 453-462.

Lenk-Chevitch. P. 1959. Beach and stream pebbles. *Jour. Geol.* **67**: 103-108.

Li, Z. and Komar. P. D. 1986. Laboratory measurements of pivoting angles for applications to selective entrainment of gravel in a current. *Sedimentology* **33**: 413-423.

Lüttig. G. 1956. Eine neue, einfache geröllmorphometrische Methode. *Eiszeitalter Gegenw.* **7**: 13-20.

Lüttig. G. 1962. The shape of pebbles in the continental. fluviatile and marine facies. *Int. Assoc. Sci. Hydrol.* **59**: 253-258.

Martini, I. P. 1977. Gravelly flood deposits of Ivene Creek. Ontario. Canada. *Sedimentology* **24**: 603-622.

McLaughlin, R. J. and Nilsen. T. H. 1982. Neogene non-marine sedimentation and tectonics in small pull-apart basins of the San Andreas fault system. Sonoma Country. California. *Sedimentology*, **29**: 865-876.

McNown, J. S. and Malaika, J. 1950. Effects of particle shape on settling velocity at low Reynolds numbers. *Am. Geophys. Un., Trans.* **31**: 74-82.

Mino, Y. 1950. On the gravel in Koromogawa, Akita Prefecture, Japan. *Sci. Rep. Tokyo Univ. Edu. Sec.* **C 2**: 91-106.

Moriyama, A. and Masui, H. 1981. *Kiso-gawa churyu bu kasho reki no keijo tokusei to orienteshon* (Morphometric features and orientations of the gravels on the bed of the middle reach of the Kiso River). *Aichi Kyoiku Daigaku Kenkyu Houkoku, Sizen Kagaku Hen (Jour. Aichi Univ. Edu. Nat. Sci.)* **30**: 1-21. *

Moriyama, A. and Mitsuno, M. 1989. The uplifting of the Kiso and Akaishi Mountain Ranges deduced from the sedimentary deposits and the Ryuto Surface in the southern Ina Valley, central Japan. *Geogr. Rev. Japan* **62A**: 691-707. **

Moriyama, A. and Nakanishi, T. 1991. Grain form characteristics and fabric orientation of pebbles in alluvial rivers. *Trans. Japanese Geomorphol. Un.* **12**: 335-355. **

Moriyama, A. and Niwa, M. 1985. Some problems on the formation of Toki Surface (Early Pleistocene) in Tono District and northwestern Mikawa Plateau, central Japan. *Geogr. Rev. Japan* **58**: 275-294. **

Nakayama, M. 1950. *Suruga-wan gan no kaihin reki ni kansuru ni san no jisho ni tsuite* (Several features on beach gravels alongshore the Suruga Bay). *Geogr. Rev. Japan* **23**: 127. *

Nakayama, M. 1952. The distribution of the size of fluvial gravels. *Geogr. Rev. Japan* **25**: 401-408. **

Nakayama, M. 1954. Roundness of pebbles of the Tama River, Kanto District. *Geogr. Rev. Japan* **27**: 497-506. **

Nakayama, M. 1960. A field study of the roundness of river pebbles. *Mem. Osaka Univ. Edu.* **A-9**: 139-156. **

Nakayama, M. 1963. On the roundness of river pebbles. *Mem. Osaka Univ. Edu.* **A-11**: 120-135. **

Nakayama, M. and Miura, T. 1964. Roundness of pebbles in the course of rivers in Japan. *Geogr. Rev. Japan* **37**: 115-130. **

Ouchi, S. 1979. A study of minor reliefs and grain size distributions on alluvial fans in central Japan. *Geogr. Rev. Japan* **52**: 190-198. **

Oyama, M. 1953. *Chosa hoho no toitsu no tameni (With special reference to the unification of survey methods).* In *Marugame Zufuku Dojo Chosa Hokokusho (Report of Soil Survey in the Marugame Alluvial Plain, Kagawa Prefecture)*, ed. Norin daijin kanbo sogo kaihatsu ka (Bureau of Comprehensive Development, Ministry of Aagriculture and Forestry, Japan), 26-27, Tokyo. *

Plletier, B. R. 1958. Pocono paleocurrents in Pennsylvania and Maryland. *Bull. Geol. Soc. Am.* **69**: 1033-1064.

Pelto, C. R. 1954. Mapping of multicomponent systems. *Jour. Geol.* **62**: 501-511.

Pettijohn, F. J. 1949. *Sedimentary Rocks. 1st Ed.* New York : Harper and Brothers.

Pettijohn, F. J. 1957. *Sedimentary Rocks. 2nd Ed.* New York : Harper and Brothers.

Plumley, W. J. 1948. Black hills terrace gravels : A study in sediment transport. *Jour. Geol.* **56**: 526-577.

Poser, H. and Hövermann, J. 1952. Beitrage zur morphometrischen und morphologischen

Schotteanalyse. *Abh. Braunschw. Wiss. Ges.* **4**: 12-36.
Powers, M. C. 1953. A new roundness scale for sedimentary particles. *Jour. Sed. Petrol.* **23**: 117-119.
Powers, M. C. 1982. Comparison chart for estimating roundness and sphericity. *AGI Data Sheet* **18**: American Geological Institute. Figure shown in Graham (1988).
Reichelt. G. 1961. Über Schotterformen und Rundungsgradanalyse als Feldmethode. *Petermanns Geogr. Mitt.* **105**: 15-24.
Rittenhouse, G. 1943. A visual method of estimating two-dimensional sphericity. *Jour. Sed. Petrol.* **13**: 79-81.
Rosfelder, A. 1960. *Contribution à l'analyse texturale des sédiments.* Unpublished M. S. thesis, University of Algiers, 356p. Cited in Flemming (1965).
Russell, R. D. and Taylor, R. E. 1937. Roundness and shape of Mississippi river sands. *Jour. Geol.* **65**: 225-267.
Sames, C. W. 1966. Morphometric data of some recent pebble associations and their application to ancient deposits. *Jour. Sed. Petrol.* **36**: 126-142.
Schneiderhöhn, P. 1954. Eine vergleichende Studie über Methoden zur quantitativen Bestimmung von Abrundung und Form an Sandkörnern. *Heidelberger Beiträg Miner. Petrog.* **4**: 172-191.
Shimazu, H. 1990. Segmentation of mountain rivers based on longitudinal change in gravel size of riverbeds in Tohoku District, Northeastern Japan. *Geogr. Rev. Japan* **63A**: 487-507. **
Sneed, E. D. and Folk, R. L. 1958. Pebbles in the lower Colorado River, Texas. A study in particle morphogenesis. *Jour. Geol.* **66**: 114-150.
Steel, R. J., Maehle, S., Nilsen, H., Roe, S. L. and Spinnangr, A. 1977. Coasening-upward cycles in the alluvium of Horneln Basin (Devonian) Norway : sedimentary response to tectonic events. *Geol. Soc. Am. Bull.* **88**: 1124-1134.
Stratten, T. 1974. Notes on the application of shape parameters to differentiate between beach and river deposits in southern Africa. *Trans. Geol. Soc. South Africa* **77**: 59-64.
Takahashi, J., Koshimura, S. and Asano I. 1987. On the gravel of river bed of the Shigenobu River, Ehime Prefecture. *Mem. Fac. Edu. Ehime Univ. Nat. Sci.* **7**: 95-120. **
Takakuwa, T. 1955. *Ikeda-wan engan no kaishoku reki* (Beach gravels alongshore the Ikeda Bay). *Kagawa Daigaku Gakugei Gakubu Chirigaku Kenkyu (Geogr. Rep. Fac. Edu. Kagawa Univ.)* **4**: 3-5. *
Takakuwa, T. and Deishi, K. 1954. *Kasen reki no rekishitsu to okisa — Kita-Shikoku ni okeru shinshokumen no kenkyu dai 1 pou—* (Particle lithology and size on the river beds —a case study of erosional surface in the northern Shikoku Island, 1st report—. *Geogr. Rev. Japan* **27**: 440-442. *
Takayama, S. 1966. Bedload movement in mountain streams (2). *Geogr. Rep. Tokyo Univ. Edu.* **10**: 113-126. **
Takei, K, Koike, M., Komai, K., Hirakoso, S. and Yaguchi, H. 1987. *Arakawa honryu no taisekibutsu* (Mainstream deposits of the Ara River). In *Arakawa. Shizen. Arakawa sogo chosa hokokusho* (The Ara River. Reports of the comprehensive studies on the Ara River, volume of natural science). ed. Saitama ken (Saitama Prefecture), 285-312. Urawa. *
Trowbridge, A. C. and Mortimore, M. E. 1925. Correlation of oil sands by sedimentary

analysis. *Econ. Geol.* **20**: 409-423.
Ueki, T. and Mitusio, T. 1998. Uplift history of the Asan Mountains, Shikoku, southwest Japan, based on stratigraphy and lithofacies of the Plio-Pleistocene Mitoyo Group. *Jour. Geol. Soc. Japan* **104**: 247-267. **
Unrug, R. 1957. Recent transport and sedimentation of gravels in the Dunajec Valley (western Carpathlans). *Acta Geol.* **7**: 217-257. ***
Wadell, H. 1932. Volume, shape, and roundness of rock particles. *Jour. Geol.* **40**: 443-451.
Wentworth, C. K. 1919. A laboratory and field study of cobble abrasion. *Jour. Geol.* **27**: 507-521.
Wentworth, C. K. 1922a. The shapes of beach pebbles. *USGS Prof. Pap.* **131-C**: 75-83.
Wentworth, C. K. 1922b. A field study of the shapes of river pebbles. *USGS Bull.* **730-C**: 103-114.
Williams, E. M. 1965. A method of indicating pebble shape in one parameter. *Jour. Sed. Petrol.* **35**: 993-996.
Yatsu, E. 1951. Preliminary study on the fluvial deposits of main rivers in Kanto-Plain — Report on the fluvial deposits No. 3—. *Geogr. Rev. Japan* **24**: 144-147. **
Yatsu, E. and Otsuka, Y. 1948. River deposits of the Tama. *Jour. Geol. Soc. Japan.* **54**: 41-43. **
Zingg, T. 1935. Beitrag zur Schotteranalyse. Die Schotteranalyse und ihre Anwendung auf die Glattalschotter. *Schweiz. Miner. Petrog. Mitt.* **15**: 39-139.

(* : in Japanese, ** : in Japanese with English abstract, *** : in Polish with English abstract)

Appendix 1 Particle form indices, conceptualizing the flatness, sphericity, elongation (oblate-prolateness), and relative uniformity of all three axes and dominant particle form. a, b, and c are the length of longest, intermediate, and shortest axes of a particle, respectively. N_{CP}, N_{CE}, N_P, N_E, N_{VP}, and N_{VE} correspond to the number of clasts in the Sneed and Folk's triangular form diagram (Appendix 2) falling in the compact platy, compact elongate, platy, elongate, very platy, and very elongate classes, respectively. N is the total number of particles examined.

Formulae	Range	Names	References
Indices of flatness			
1. $\frac{a+b}{2c}$	0—∞	Wentworth flatness	Wentworth (1922a); Cailleux (1945, 1947)
2. $\frac{b-c}{b}$	0—1	Nakayama flatness	Nakayama (1950); Takakuwa (1955)
3. $\frac{c}{a}$	0—1	Lüttig flatness 1)	Lüttig (1956); Sneed and Folk (1958); Illenberger (1992)
4. $\frac{c}{b}$	0—1	Illenberger flatness 2)	Illenberger (1992)
5. $\frac{a-b+c}{a}$	0—1	Modified Hockey flatness 3)	Illenberger (1992); Illenberger and Reddering (1993)
Indices of sphericity			
6. $\sqrt[3]{\frac{bc}{a^2}}$	0—1	Intercept sphericity 4)	Krumbein (1941a, 1942b)
7. $\frac{c}{\sqrt{ab}}$	0—1	Corey Portance 5)	Corey (1949); McNown and Malaika (1950); Goguel (1953) Takayama (1966)
8. $\sqrt[3]{\frac{c^2}{ab}}$	0—1	Maximum projection sphericity 6)	Folk (1955); Sneed and Folk (1958)
9. $\frac{12.8\cdot\sqrt{\left(\frac{c}{b}\right)^2\cdot\left(\frac{b}{a}\right)}}{1+\left(\frac{c}{b}\right)\cdot\left(1+\left(\frac{b}{a}\right)+6\cdot\sqrt{1+\left(\frac{c}{b}\right)^2\cdot\left(1+\left(\frac{b}{a}\right)^2\right)}\right)}$	0—0.96	Working sphericity	Aschenbrenner (1956)
10. $c\cdot\sqrt{\frac{3}{a^2+b^2+c^2}}$	0—1	E-shape factor	Janke (1966)
11. $\frac{a}{b}+\frac{a}{c}$	2—∞	Extremeness	Janke (1966)
12. $\frac{c}{a+b+c}$	0—0.3	Proportion of the shortest axis 7)	Hofmann (1994)
Indices of elongation			
13. $\frac{b}{a}$	0—1	Folk elongation 8)	Folk (1955); Lüttig (1956); Illenberger (1991)
14. $\frac{\sqrt{bc}}{a}$	0—1	Krumbein elongation	Krumbein (1939)
15. $\frac{ac}{b^2}$	0—∞	Aschenbrenner shape factor	Aschenbrenner (1956)
16. $\frac{a-b}{a-c}$	0—1	Disk-rod index 9)	Sneed and Folk (1958)

Continued to the next page

17. $\begin{cases} 1-\frac{ac}{b^2} & (b^2>ac) \\ \frac{b^2}{ac}-1 & (b^2 \leq ac) \end{cases}$	-1—1	Williams shape factor 10)	Williams (1965)
18. $\frac{\frac{a-b-0.5}{a-c}}{\frac{c}{a}}$	-∞—∞	Oblate-prolate index	Dobkins and Folk (1970)
19. $\frac{b+c}{a}$	0—2	Rod index	Illenberger (1991)
20. $\frac{a+c}{b}$	1—∞	Isometry	Flemming (1965); Illenberger (1991)
21. $\frac{b}{a+b+c}$	0—0.5	Proportion of the intermediate axis 11)	Hofmann (1994)
22. $\frac{a-b}{a+b+c}$	0—1	Axial difference in the maximum projection plane 11)	Hofmann (1994)
Indices of relative uniformity of all three axes			
23. $\frac{-\sum_i (P_i \cdot \ln(P_i))}{1.0986}$ $P_i=\frac{i}{\Sigma i}$ i=a, b, c	0—1	Relative axial entropy	Pelto (1954); Forgotson (1960)
24. $\begin{cases} 1-((P_a-P_b)-(P_b-P_c)) & (P_a-P_b>P_b-P_c) \\ 1-((P_b-P_c)-(P_a-P_b)) & (P_a-P_b<P_b-P_c) \end{cases}$ $P_i=\frac{i}{\Sigma i}$ i=a, b, c	0—1	Classifying-function (D-function) 12)	Pelto (1954)
25. $\sqrt{(1.15\times((1/3)-P_b-0.5\times(P_a-(1/3)))^2+(P_a-(1/3))^2}$ $P_i=\frac{i}{\Sigma i}$ i=a, b, c	0—0.67	Distance-distribution function	Krumbein (1955)
Other form index			
$\frac{(N_{CP}-N_{CE})+2\cdot(N_P-N_E)+4\cdot(N_{VP}-N_{VE})}{2\cdot N}$	-∞—∞	Form ratio 13)	Sneed and Folk (1958)

Remarks

1) Originally named roundness (Wadell 1932; Flemming 1965) or sphericity (Illenberger 1992; Hofmann 1994; Hattingh and Illenberger 1995).

2) First proposed by Zingg (1935). Poser and Hövermann (1952) designated the reciprocal of this index as flatness. Li and Komar (1986) and Hofmann (1994) designated as pivotability. Hofmann (1994) also designated as rollability.

3) Modified after Hockey (1970).

4) Based on the true sphericity proposed by Wadell (1932).

5) McNown and Malaika (1950), and Goguel (1953) designated as flatness and sphericity, respectively. Takayama (1966) designated the reciprocal of this index as flatness.

6) Rosfelder (1960) designated the reciprocal of this index as portance.

7) Designated in this study. Not multiplied by 100.

8) First proposed by Zingg (1935). McNown and Malailka (1950) and Poser and Hövermann (1952) designated the reciprocal of this index as circularity and slenderness, respectively.

9) Designated in Illenberger (1991). Bradley *et. al* (1972) designated as elongation.

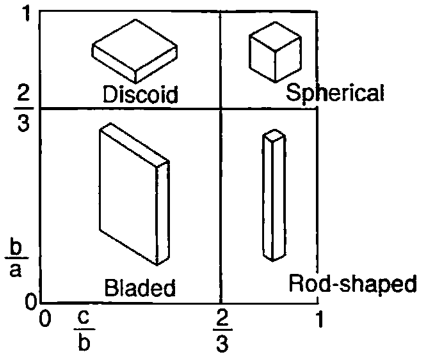
10) Modified after the shape factor "F" in Aschenbrenner (1956).

11) Designated in this study. Not multiplied by 100.

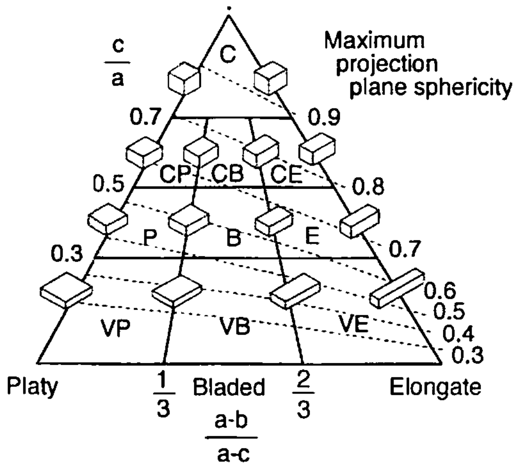
12) Not multiplied by 100 in this study.

13) Form ratio implies the degree of elongation, not based on the three perpendicular axial length.

Appendix 2 Particle form diagrams after Zingg (1935), and Sneed and Folk (1958). Zingg diagram shows the relationships between the axial ratios of b/a and c/b, and is subdivideed into four form classes indicative of spherical, discoid, rod-shaped and bladed particles. Sneed and Folk triangular form diagram shows the relationships between the axial ratios of c/a and (a-b)/(a-c), and indicates subdivided ten form classes. The classes of C, CP, CB, CE, P, B, E, VP, VB and VE defined on the diagram characterize compact, compact platy, compact bladed, compact elongate, platy, bladed elongate, very platy, very bladed and very elongate particles, respectively. Dashed lines are those of constant maximum-projection-sphericity of particles.



1. Zingg form diagram



2. Sneed and Folk triangular form diagram