PERGAMON

Journal of Structural Geology 21 (1999) 473–478

JOURNAL OF STRUCTURAL GEOLOGY

Roundness of clasts in pseudotachylytes and cataclastic rocks as an indicator of frictional melting

Aiming Lin*

Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

Received 17 February 1998; accepted 9 November 1998

Abstract

We examine the roundness (Rd) of clasts derived from fault rocks and discuss its possible application as an indicator for fracturing and chipping or frictional melting. The roundness of quartz and feldspathic clasts derived from four frictional melting-originated pseudotachylytes and one crushing without melting-originated pseudotachylyte as well as three cataclastic rocks was measured. Between 230 and 270 clasts >10 μm in size were measured for each sample. The analyses show that Rd is lower than 0.4 in all the clasts included in the cataclastic rocks and crushing-originated pseudotachylyte, whereas it varies from 0.1 to 1.0 and 35–90% of clasts have a roundness >0.4 in the melting-originated pseudotachylyte. It is suggested that the clasts having a roundness >0.4 were rounded by frictional melting rather than by fracturing or chipping in pseudotachylytes, and that the roundness of clasts may be used as a special index of disintegration attributed to attrition and melting.

1. Introduction

Fault-related pseudotachylytes found as simple veins and injected networks in fault zones are widely considered to be earthquake ‘fossils’ recording the events of seismic slip. These rocks generally comprise an ultrafine-grained and generally dark matrix containing various sizes of comminuted lithic clasts (i.e. Philpotts, 1964; Sibson, 1975; Magloughlin, 1992; Lin, 1994a, b). The melting origin of pseudotachylyte has been demonstrated by field and petrologic studies (i.e. Sibson, 1975; Maddock, 1983; Spray, 1987; Lin, 1991, 1994a, b). Experimental results also show that melt-originated pseudotachylyte can be generated by frictional heating at depths as shallow as several tens of metres (Spray, 1987, 1992, 1995; Lin, 1991; Lin and Shimamoto, 1999). However, it has also been reported, recently that some pseudotachylytes are dark and aphanitic and show the occurrences of simple veins and complex networks injected in the wallrocks have an origin by crushing, not melting (Lin, 1996, 1997; Lin et al., 1998). There is a general character between the melting- and crushing-originated pseudotachylytes, in that these rocks consist of ultrafine-grained matrix and various sizes and shapes of lithic clasts and occur as simple veins and injected networks. The rounded and embayed clasts set in matrices in pseudotachylytes are generally considered to be indicative of melting rather than crushing origin (e.g. Shand, 1916; Philpotts, 1964; Sibson, 1975; Wallace, 1976; Allen, 1979; Maddock, 1983; Lin, 1991, 1994a, b, 1996; Magloughlin, 1992). Rounded clasts have also been documented in ultracataclasites (e.g. Chester et al., 1993). However, the roundness and embayment of clasts were only described qualitatively and not evaluated quantitatively as evidence of melting.

The aim of this study is to analyze the roundness of lithic clasts included in several of the better-studied pseudotachylytes and cataclastic rocks in order to derive quantitative index relationships between pseudota-

* Correspondence address: Department of Earth and Planetary Sciences, Faculty of Science, Kobe University, Kobe 657-8501, Japan.

E-mail address: lin@kobe-u.ac.jp (A. Lin)

0191-8141/99/$ - see front matter
PII: S0191-8141(99)00030-9

Table 1
Samples of pseudotachylytes (Pt) and cataclastic rocks used in this study

Sample location	Sample type	References
Outer Hebrides Thrust, Scotland	Melting-originated Pt	Sibson (1975)
Musgrave range, Australia	Melting-originated Pt	Shimamoto and Nagahama (1992)
Fuyun fault zone, China	Melting-originated Pt	Lin (1991, 1994a, b)
Osumi Shear zone, Japan	Melting-originated Pt	Fabbri et al. (1997)
Iida–Matsukawa fault, Japan	Cataclasite	Lin (1996, 1997)
Iida–Matsukawa fault, Japan	Fault breccia–Microbreccia	Lin (1996, 1997)
Iida–Matsukawa fault, Japan	Crushing-originated Pt	Lin (1996, 1997)
Nojima fault, Japan	Fault gouge	Lin et al. (1998)

chylytes and cataclastic rocks for understanding the process and mechanism of pseudotachylyte formation.

2. Measurement of clast roundness

2.1. Samples

Two types of samples (Table 1) are used for analysis of roundness of clasts in this study: one is the well-known melting-originated pseudotachylytes (Sibson, 1975; Shimamoto and Nagahama, 1992; Lin, 1994a, b; Fabbri et al., 1997); the other is the crushing-originated pseudotachylytes and cataclastic rocks (Lin, 1996, 1997; Lin et al., 1998). The fault gouge samples were taken from drill core from the Nojima fault along which surface rupture occurred during the 1995 Southern Hyogo Prefecture Earthquake (M7.2), Japan (Lin and Uda, 1996). The host rocks of all samples analyzed in this study are granitic, which are mainly composed of quartz and feldspar crystals. The measurements of roundness were performed on the quartz and feldspar clasts for avoiding the effect of hardness of different minerals on the roundness and also for convenience.

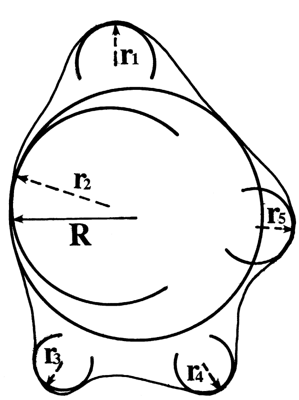

Fig. 1. Illustration of the roundness (Rd) of clasts, where r is the radius of curvature of the corner and R is the radius of the maximum inscribed circle in the plane of measurement.

2.2. Analysis method

The shape of solid particles or clasts is often used as an indicator to evaluate the transfer process and sediment environment in sedimentology (Wadell, 1932; Research Group of Sedimentary Rocks of Japan, 1983) and to evaluate the deformation process in fault-related rocks (e.g. Lin, 1991). In order to quantitatively evaluate the shape of clasts, we measure roundness of clasts. Roundness (Rd) is defined by Wadell (1932) in one plane (Fig. 1) as

$$\mathrm{Rd} = \sum(\mathrm{ri}/R)/n \qquad (1)$$

where ri is the radius of curvature of the corner, R is the radius of the maximum inscribed circle in the plane of measurement, and n is the number of the corners of clasts in the given plane. The maximum value for roundness achieved by this formula is 1.0. Images of the clast roundness (Krumbein, 1941) is shown in Fig. 2. The roundness of clasts measured and calculated in this study is also checked by comparing with this image.

Measurements of roundness were conducted on photomicrographs of the samples taken under plane polarized light and in SEM (Fig. 3). The matrix of the melting-originated pseudotachylytes is light to dark brown, whereas the quartz and feldspathic clasts appear white to colourless under plane polarized light (Fig. 3a–d). The quartz and feldspathic clasts in the cataclastic rocks and the crushing-originated pseudotachylyte can also be distinguished easily with other mineral clasts on the photomicrographs (Fig. 3e–h). It is difficult to distinguish completely the quartz and feldspathic clasts on the photomicrographs; thus, the measurements were performed on both minerals. The measurement precision of the radius of curvature of the corner is usually affected by the size of clasts. In order to avoid such measurement error caused by size, the measurements were performed on a wide area for all clasts larger than 10 μm in diameter. The roundness of clasts was calculated by the formula (1) and also

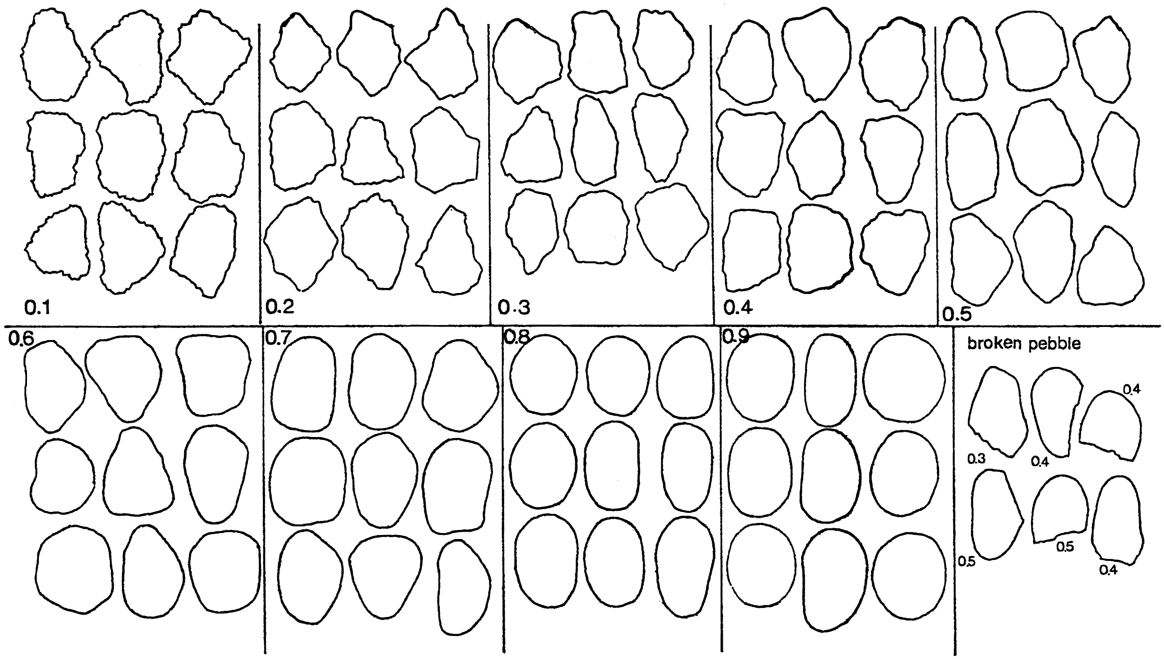

Fig. 2. Image graph of the roundness (Rd) of fragments. Value of Rd varies from 0.1 to 1.0.

checked by comparing with the image graph (Fig. 2) to avoid biased measurements.

2.3. Results

The results were plotted as roundness–frequency diagrams (Fig. 4). The roundness varies from 0.0 to 1.0 (Fig. 4a–d). From 35 to 90% of the clasts included in the melting-originated pseudotachylytes have a roundness >0.4, whereas all the clasts included in the crushing-originated pseudotachylytes (Fig. 4g) and the cataclastic rocks (Fig. 4e, f, h) have a roundness <0.4, in which 80–95% of the clasts have a roundness <0.3. It is clear that there is a difference in roundness between the melting-originated pseudotachylytes and the cataclastic rocks.

3. Discussion

Rounded and embayed clasts were considered one of the characteristics due to melting in pseudotachylytes (e.g. Shand, 1916; Philpotts, 1964; Sibson, 1975; Maddock, 1983; Lin, 1991, 1994a, b; Magloughlin, 1992). The clasts that occur within fault zones provide primary evidence for the deformation process that occurs there. Thus, the roundness of clasts included in the fault rocks is one of the indicies of the process, and a high degree of roundness is, therefore, probably an indication of general conditions of wear or melt relative to size and hardness of the clasts. The roundness of clasts included in the fault zone is probably affected by fracturing, chipping, and melting during faulting and also probably by chemical solution of groundwater.

Shape fabrics of clasts are often reported from natural cataclastic rocks (e.g. Anderson et al., 1983; Mitra, 1984; Chester and Logan, 1986; Sammis et al., 1987; Evans, 1988; Chester et al., 1993; Evans and Chester, 1995). By comparing the shape of clasts derived from cataclastic rocks (plate IIa in Anderson et al., 1983; fig. 5d in Chester and Logan, 1986; figs. 4–8 in Sammis et al., 1987; fig. 1a in Evans, 1988) and from the crushed grains generated by triaxial compression experiment (figs. 5–6 in Menendez et al., 1996) with Fig. 2, it is estimated that all these clasts >10 μm have a roundness <0.4, although the roundness cannot be exactly measured. This means that roundness >0.4 of clasts is difficultly formed by fracturing or chipping.

The measurements of the roundness were performed on quartz and feldspathic clasts >10 μm in diameter in all the samples as stated above. Surface textures of clasts included in fault gouges are generally affected by groundwater (Kanaori, 1983). Based on the surface smoothness of quartz grains from 250 fault gouge samples derived from 14 main faults in Japan, Kanaori (1983) categorized quartz grains into four groups from I to IV. These were suggested to be formed by the progressive corrosion and solution of groundwater during the periods of fault movement from the Late Pleistocene to the Miocene which are estimated from geological evidence. Similar surface shapes of quartz grains derived from fault gouges of

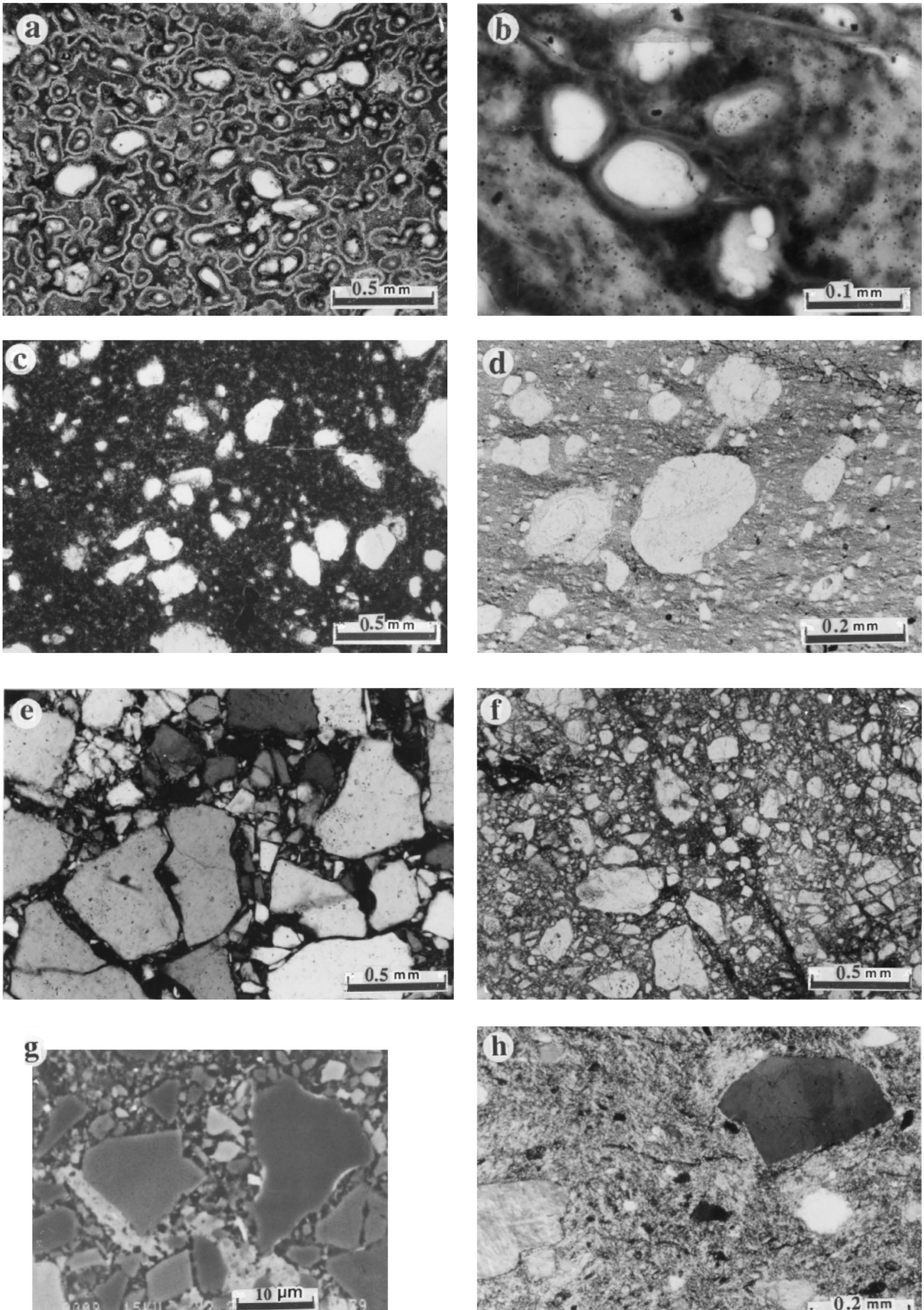

Fig. 3. Photomicrographs showing the textures of rounded clasts included in the melting-originated pseudotachylytes (Pt) (a–d) and cataclastic rocks (e–h). (a) Fuyun Pt, China. (b) Outer Hebrides Pt, Scotland. (c) Musgrave Pt, Australia. (d) Osumi Pt, Japan. (e) Iada–Matsukawa cataclasite, Japan. (f) Iida–Matsukawa fault breccia–microbreccia, Japan. (g) Iida–Matsukawa crushing-originated Pt, Japan. (h) Nojima fault gouge, Japan. (a–f) Plane polarized light. (g) SEM. (h) Crossed polarized light.

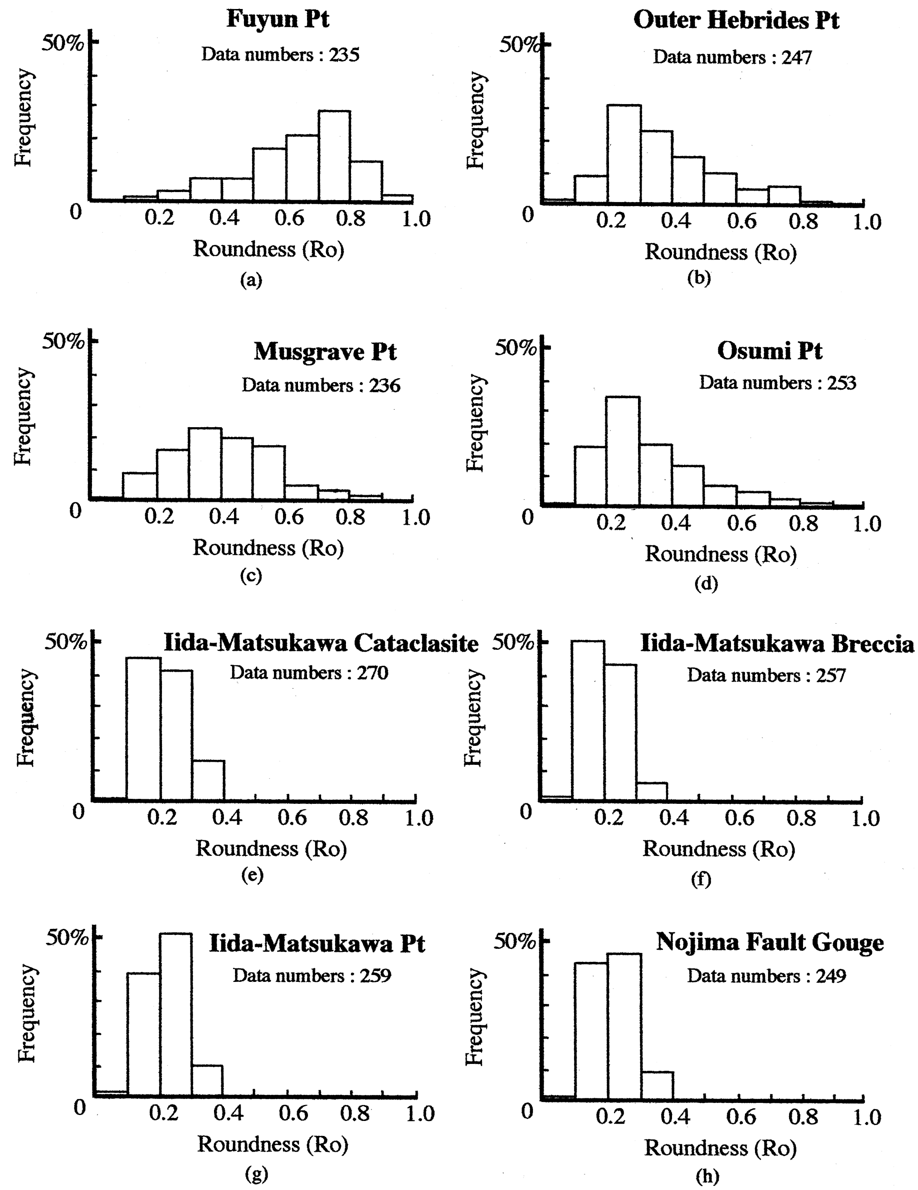

Fig. 4. Roundness–frequency diagram showing the roundness of clasts. Parts (a–d) melting-originated pseudotachylyte (Pt). Parts (e–h) cataclastic rocks. (a) Fuyun Pt, China. (b) Outer Hebrides Pt, Scotland. (c) Musgrave Pt, Australia. (d) Osumi Pt, Japan. (e) Iida–Matsukawa cataclasite, Japan. (f) Iida–Matsukawa fault breccia–microbreccia, Japan. (g) Iida–Matsukawa crushing-originated Pt, Japan. (h) Nojima fault gouge, Japan.

several main active faults in China were also reported in Yang (1986). The shapes of these grains included in the four groups were compared with Fig. 2 in this study. All these quartz grains have a roundness < 0.3. Thus, it is impossible that the clasts having a roundness > 0.4 were formed by the corrosion and solution of groundwater in fault zones.

The measured results in this study show that 35–90% of the clasts included in the well-known melting-originated pseudotachylytes have a roundness > 0.4, whereas all those with a roundness < 0.4 originated by cataclasis. This strongly suggests that clasts with a roundness > 0.4 were formed by melting rather than fracturing or chipping. The rounded clasts in pseudotachylytes can be explained to be formed by frictional melting. Sibson (1975) suggested that the rounding of clasts in pseudotachylytes was formed by marginal decrepitation of angular clasts in a liquid phase. By simple conduction theory, he explained that the isothermal surface of angular clasts, while in general subparallel to cooling surface or contacts, will tend to be 'rounded off' adjacent to sharp angular projections and corners (fig. 5 in Sibson, 1975).

By the documentation above, it is suggested that the lithic clasts included in pseudotachylytes having a roundness > 0.4 were rounded by melting rather than fracturing or chipping, and that the roundness can be used as an index for evaluating the formation process of pseudotachylytes.

Acknowledgements

I would like to express my sincere thanks to Professors T. Shimamoto (now in Kyoto University) and T. Matsuda (now in Seinangakuin University) of the University of Tokyo for their advice and support throughout this study. I thank Dr. T. Arai of the University of Tokyo for providing the samples. Thanks to Dr. J. Evans and Dr. J. Spray for their constructive comments and suggestions which helped improve the manuscript.

References

Allen, A.R., 1979. Mechanism of frictional fusion in fault zones. Journal of Structural Geology 1, 231–243.

Anderson, J.L., Osborne, R.H., Palmer, D.F., 1983. Cataclastic rocks of the San Gabriel fault—An expression of deformation at deeper crustal levels in the San Andreas fault zone. Tectonophysics 98, 209–251.

Chester, F.M., Logan, J.M., 1986. Implication for mechanical properties of brittle faults from observations of the Punchbowl fault zone, California. Pure and Applied Geophysics 124, 80–106.

Chester, F.M., Evans, J.P., Biegel, R., 1993. Internal structure and weaking mechanisms of the San Andreas fault. Journal Geophysical Research 98, 771–786.

Evans, J.P., 1988. Deformation mechanisms in granitic rocks at shallow crustal levels. Journal of Structural Geology 10, 437–443.

Evans, J.P., Chester, F.M., 1995. Fluid–rock interaction in faults of the San Andreas system: Inferences from San Gabriel fault rock geochemistry and microstructures. Journal Geophysical Research 100, 13007–13020.

Fabbri, O., Kano, T., Lin, A., 1997. Occurrence of pseudotachylytes in the Miocene Osumi grandioritic pluton (Kyushu Japan). Abstract of the 104th Annual Meeting of the Geological Society of Japan.

Kanaori, Y., 1983. Fracturing mode analysis and relative dating of faults by surface textures of quartz grains from fault gouges. Engineering Geology 19, 261–281.

Krumbein, W.C., 1941. Measurement and geologic significance of shape and roundness of sedimentary particles. Journal of Sedimentary Petrology 11, 64–72.

Lin, A., 1991. Origin of fault-generated pseudotachylites. Ph.D. thesis, the University of Tokyo.

Lin, A., 1994a. Glassy pseudotachylytes from Fuyun fault zone, northwest China. Journal of Structural Geology 16, 71–83.

Lin, A., 1994b. Microlite morphology and chemistry in pseudotachylite, from the Fuyun Fault Zone, China. Journal of Geology 102, 317–329.

Lin, A., 1996. Injection veins of crushing-originated pseudotachylyte and fault gouge formed during seismic faulting. Engineering Geology 43, 213–224.

Lin, A., Uda, S., 1996. Morphological characteristics of the earthquake surface ruptures on Awaji Island, associated with the 1995 Southern Hyogo Prefecture earthquake. The Island Arc 5, 1–15.

Lin, A., 1997. Fluidization and rapid injection of crushed fine-grained materials in fault zones during episodes of seismic faulting. In: Zheng et al (Ed.), Proceedings of the 30th International Geological Congress, vol. 14. VSP, pp. 27–40.

Lin, A., Shimamoto, T., 1999. Selective melting process as inferred from experimentally-generated pseudotachylytes. Journal of Asian Earth Sciences 16, 533–545.

Lin, A., Shigetomi, M., Shimamoto, T., Miyata, T., Takemura, K., Tanaka, H., Uda, S., Murata, A., 1998. Neotectonic history of the Nojima fault zone reversed by fault rock fabrics (in Japanese). Gekkan Chikyu 21, 208–212.

Maddock, R.H., 1983. Melt origin of fault-generated pseudotachylytes demonstrated by textures. Geology 11, 105–108.

Magloughlin, J.F., 1992. Microstructural and chemical changes associated with cataclasis and frictional melting at shallow crustal levels: the cataclasite–pseudotachylyte formation. Tectonophysics 204, 243–260.

Menendez, B., Zhu, W., Wong, T., 1996. Micromechanics of brittle faulting and cataclastic flow in Berea sandstone. Journal of Structural Geology 18, 1–16.

Mitra, G., 1984. Brittle to ductile transition due to large strains along the White Rock thrust, Wind River mountains, Wyoming. Journal of Structural Geology 6, 51–61.

Philpotts, A.R., 1964. Origin of pseudotachylites. American Journal of Science 259, 542–550.

Research Group of Sedimentary Rocks of Japan, 1983. Study method of sedimentary rocks—conglomerate, sandstone, and mudstone. Research Group of Geoscience (Eds.), Chigakushoshyo, Tokyo (in Japanese).

Shand, S.J., 1916. The pseudotachylyte of Parijs (Orange Free State), and its relation to 'trap-shoten gneiss' and 'flinty crush-rock'. Quarter Journal of Geological Society of London 72, 198–221.

Shimamoto, T., Nagahama, H., 1992. An argument against the crush origin of pseudotachylytes based on the analysis of clast-size distribution. Journal of Structural Geology 14, 999–1006.

Sibson, R.H., 1975. Generation of pseudotachylite by ancient seismic faulting. Geophysical Journal of the Royal Astronomical Society 43, 775–794.

Sammis, C., King, G., Biegel, R., 1987. The kinematics of gouge deformation. Pure and Applied Geophysics 125, 777–812.

Spray, J.G., 1987. Artificial generation of pseudotachylyte using friction welding apparatus. Contributions to Mineralogy and Petrology 99, 464–475.

Spray, J.G., 1992. A physical basis for the frictional melting of some rock-forming minerals. Tectonophysics 205, 19–34.

Spray, J.G., 1995. Pseudotachylyte controversy: Fact or fiction? Geology 23, 1119–1123.

Wadell, H.A., 1932. Volume, shape, and roundness of rock particles. Journal of Geology 40, 1074–1106.

Wallace, R.C., 1976. Partial fusion along the Alpine Fault Zone, New Zealand. Geological Society of America Bulletin 87, 1225–1228.

Yang, Z., 1986. Study on the model of ductile–brittle transformation—A geological process of propagation for shallow tectonic earthquake source. Ph.D. thesis, Institute of Geology, State Seismological Bureau of China.