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ORIGINAL PAPER

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Pseudotachylite on impact marks of block surfaces in block-and-ash flows at Merapi volcano, Central Java, Indonesia

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Abstract Surfaces of meter-sized blocks in the 1998 block-and-ash flow deposits of Merapi volcano are partially covered by centimeter-sized, randomly orientated impact marks, which consist of an outer, glassy pseudotachylite underlain by a cataclastic layer. Whole rock, pseudotachylite, melt inclusion in plagioclase and host rock groundmass compositions indicate that the pseudotachylite was generated by remelting of bulk rock on block impact. The occurrence and distribution of this new type of collision-related pseudotachylite on volcanic block surfaces demonstrate that blocks were transported by chaotic rotation, saltation and tumbling. The random orientation of impact marks suggests grain flow as the dominant process rather than any other currently discussed pyroclastic flow mechanism. In addition, the chaotic orientation of striations is interpreted as reflecting momentum transfer having been dominated by short-lived intergranular collisions. The blocks have apparently been transported in the collisional regime of grain flow.

Keywords Pseudotachylite · Impact marks · Frictional melting · Block-and-ash flows · Merapi volcano

Introduction

Long periods of lava dome growth accompanied by dome collapse that result in small-volume pyroclastic flows, so-called block-and-ash flows, are characteristic of the ongoing activity of Merapi volcano. These flows consist of valley-filling, ground-hugging basal avalanches and overriding ash clouds. The bulk of pyroclastic debris is transported in avalanches – rapid, gravity-driven mixtures of hot volcanic particles and juvenile and/or entrained gas.

The mode of transport of pyroclastic flows is the subject of intense debate. Grain flow (e.g. Yamamoto et al. 1993), fluidized flow (e.g. Sparks 1976) and expanded turbulent flow (e.g. Fisher et al. 1993) have been discussed as potential pyroclastic flow mechanisms (cf. review by Freundt and Bursik 1998). Currently proposed fundamental rheological flow models are viscoplastic and turbulent models (e.g. Sousa and Voight 1995), the sliding block model (e.g. Hayashi and Self 1992), and the rapid granular flow model (e.g. Straub 1996; cf. review by Druitt 1998).

Several structures in the basal avalanche deposits that erupted from Merapi volcano in 1998, such as pronounced reverse grading of coarse clasts and their orientation in flow direction, are characteristic of density-modified grain flows, and appear to be common for small-volume pyroclastic flows (e.g. Moore and Melson 1969; Rose et al. 1977; Nairn and Self 1978; Boudon et al. 1993; Yamamoto 1993). In grain flows, two distinctive end-member flow regimes were recognized by Drake (1990). One is the frictional regime, in which momentum is transferred by enduring frictional contact between particles, the other is the collisional regime, in which momentum transfer results from collisions between particles. Here, we report on the occurrence of impact marks on block surfaces in block-and-ash flow deposits in order to contribute to the current discussion on flow models.

The impact marks consist of a pseudotachylite layer on a cataclastic zone on the surfaces of large blocks deposited by block-and-ash flows. Pseudotachylite was first described by Shand (1916) to characterize tachylite-like dark veins in the Vredefort structure in South Africa. Since then, the occurrence of natural pseudotachylites has been reported from faults (e.g. Swanson 1992; Spray 1995), meteorite impact structures (e.g.

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Magloughlin and Spray 1992; Spray and Thompson 1995) and landslides (e.g. Mash et. al. 1985).

Here, we introduce a new type of collision-generated pseudotachylite formed by impact-induced bulk rock melting. Occurrences of this type have very recently been reported independently by Schwarzkopf and Schmincke (2000) and Sparks et al. (2000) from block-and-ash flow deposits of Merapi and Soufriere Hills volcano on Montserrat, respectively. The chemical compositions of (1) the groundmass of the host rock, (2) melt inclusion glass in feldspar phenocrysts and (3) pseudotachylite glass were studied by electron microprobe in order to find out if the glassy pseudotachylite has been produced by collisional melting or if the collision glass represents residual liquid squeezed out of the rock's interior.

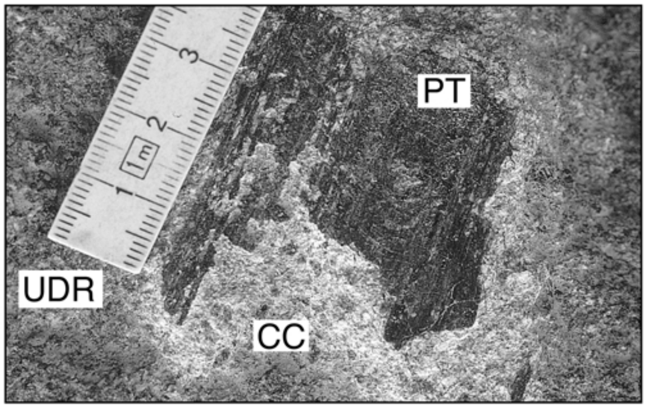


Fig. 1 Impact mark on block-surface in the block-and-ash flow deposits of the 1998 eruption of Merapi volcano showing the undisturbed rock (*UDR*), the cataclasite (*CC*) and the pseudotachylite (*PT*) (*scale* in cm)

Analytical methods

Minerals and glasses were analyzed with a Cameca SX-50 electron microprobe (EMP) at GEOMAR, applying the built-in PAP correction procedure (Pouchou and Pichoir 1984). Analytical conditions included an acceleration voltage of 15 kV, a beam current of 8–20 nA, and counting times of between 20 and 60 s on peaks. A focused beam was used for feldspar, and a rastered beam of ca. 80 μm^2 for melt inclusions and 140 μm^2 for matrix glass and pseudotachylite. Natural and synthetic minerals were used as standards and monitors. Analytical accuracy is <0.3% for concentrations of >10 wt% and <5% for 0.1–10 wt%. XRF analyses of whole rocks were performed on a Phillips PW 1480 at GEOMAR, using natural standards. Textures were examined by means of optical microscopy, using thin sections oriented parallel and normal to striations on pseudotachylite faces. Scanning electron microscope (SEM) investigations of pseudotachylite were carried out on a Camscan SC 24 compact at GEOMAR.

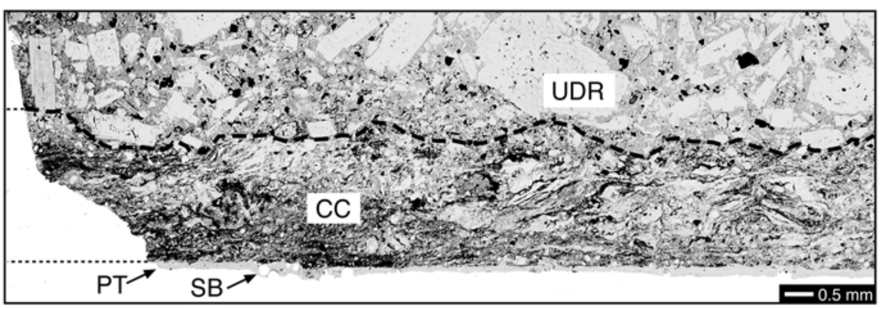
Description of the impact marks

Basal avalanche deposits of the 1998 eruptions of Merapi volcano consist of subangular to subrounded, fairly dense blocks (up to 20 m in size) and a matrix of lapilli and ash. Surfaces of meter-sized blocks show randomly orientated impact marks up to 30 cm in length and 6 cm in width on all sides of a block (Fig. 1).

The marks consist of an up to 6-mm-thick cataclastic layer of crushed rock coated by a glassy pseudotachylite. The contact to the undisturbed host rock is sharp; however, there is a gradual decrease in grain-size within the cataclasite towards the glassy pseudotachylite (Fig. 2).

The cataclasite is roughly to smoothly foliated by spaced and discontinuous bands of opaque dust and platy crystal fragments aligned parallel to the surface. The cataclasite consists of up to 20 vol% subangular to subrounded and lensoid rock fragments up to 0.5 mm in size embedded in a fine-grained matrix. Rock fragments consist mainly of undisturbed host rock fragments, many fragments having been deformed and rotated. Fragments of plagioclase are subangular, and grain sizes range from less than 0.02 to 0.8 mm, contrasting with plagioclase crystals in the undisturbed rock ranging from 0.1 to 2.5 mm. Some

Fig. 2 Photomicrograph of an impact mark. Note decreasing grain-size from undisturbed rock (*UDR*; *top*) towards cataclasite (*CC*) and pseudotachylite (*PT*; *bottom*). The cataclasite shows a rough to smooth, spaced and discontinuous foliation and grades into a homogeneous, bubble-bearing (*SB*) pseudotachylite glass. Section parallel to striations on the pseudotachylite



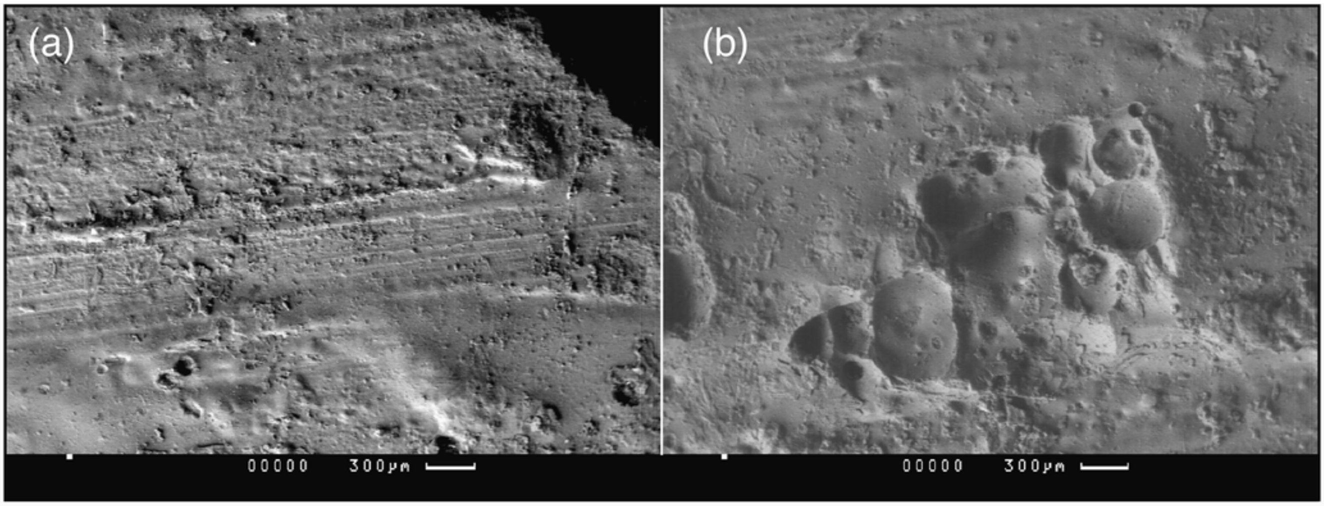


Fig. 3 SEM pictures of pseudotachylite surfaces. **a** Striations show smooth appearance at the surface. Note burst bubble craters on the *lower left*. **b** Burst bubble craters represent substantial degassing on remelting

plagioclase grains show undulose extinction and internal microfracturing.

Commonly, an outer glassy layer of pseudotachylite, ca. 0.1 to 0.5 mm thick, covers the cataclasite. The contact between pseudotachylite and cataclasite is sharp. The pseudotachylite layer itself consists of homogeneous glass, and its polished surface shows distinctive striations (Fig. 3).

Striation surfaces are smooth; V-shaped mechanical patterns are absent. Adhering micron-sized material is abundant. Spherical bubbles with diameters of up to 0.4 mm are common in the pseudotachylite rind, some of which having clearly formed after the striation was produced, as evidenced by burst bubble craters (Fig. 3b).

Composition

Melt inclusions in zoned plagioclase, groundmass of the undisturbed rock and the pseudotachylite glass were analyzed by EMP. Whole rock data from samples of the 1998 eruption are taken to represent the general bulk compositions of recent Merapi rocks. These range from basaltic andesite to andesite and are highly porphyritic. Phenocrysts are mainly plagioclase, clinopyroxene and Fe-Ti-oxides with minor amphibole and orthopyroxene.

The whole rock samples, melt inclusions and groundmass are chemically related, plotting within a single evolutionary sequence (Table 1, Fig. 4).

This is indicated by enrichment of alkalis and SiO_2 coupled with a decrease in FeOt, MgO, and CaO. In all cases, major element concentrations of pseudotachylite glasses plot in a field widely overlapping that of whole rock samples and primitive melt inclusions. Significantly lower Cl-content (Fig. 4c) of pseudotachylite (0 to 1,100 ppm Cl, mean 500 ppm), strongly contrasting with the higher Cl-content of the groundmass (200 up to 2,500 ppm, mean 1,200 ppm) and the melt inclusions (1,100 up to 7,400 ppm, mean 5,600), reveal Cl-loss during formation of pseudotachylite.

These results allow us to infer severe degassing of the pseudotachylite impact melt on crushing and remelting. F-contents, in turn, are low in melt inclusions and groundmass but are elevated in pseudotachylite glass. This is interpreted as the result of amphibole fractionation depleting F in melt inclusion and groundmass, whereas higher F-content in pseudotachylite glass is caused by amphibole being a constituent of the whole rock melt formed during impact.

Discussion

Generation of impact marks

Pseudotachylite and whole rocks have similar compositions, indicating that the pseudotachylite has been generated by bulk-rock remelting. Melting was accompanied by degassing forming spherical, non-deformed bubbles. Thus bubble formation took place following collision and formation of striations, as revealed by burst bubbles intersecting surface striations.

Frictional melting is widely accepted as a major mechanism for the generation of pseudotachylite (Magloughlin and Spray 1992). High-speed slip experiments (up to 2 m/s) by Spray (1995) show that comminution is an essential precursor to frictional melting following a specific sequence of (1) initial fracturing, (2) surface volume increase by continued comminution and (3) melting due to heat generation by fracture and elastic deformation of progressively crushed fragments. Generation of pseudotachylite described here is thought to be largely in accordance with the sequence suggested by Spray (1995).

Table 1 Representative whole rock, pseudotachylite, melt inclusion and groundmass analyses. Whole rocks were analyzed with XRF, whereas pseudotachylite, melt inclusion glass and groundmass were analyzed by EMP (*n.a.* not analyzed)

	Whole Rocks			Pseudotachylites		
Sample no.	98–52	99–135	99–163	C-5 PT-gl1	C-9 Pt-gl2	C-15 PT-gl2
SiO_2	55.58	55.29	55.29	54.30	54.35	54.85
TiO_2	0.72	0.74	0.74	0.95	0.85	0.77
Al_2O_3	19.42	19.93	19.11	19.52	19.55	19.31
FeO	7.69	7.81	7.88	7.72	7.14	7.11
MnO	0.19	0.18	0.20	0.24	0.28	0.28
MgO	2.25	2.13	2.25	2.57	2.67	3.00
CaO	8.26	8.20	8.38	8.62	8.85	8.87
Na_2O	3.46	3.41	3.50	3.52	3.51	3.58
K_2O	2.15	1.99	2.13	1.90	1.90	1.86
P_2O_5	0.30	0.34	0.31	0.44	0.42	0.42
F	n.a.	n.a.	n.a.	0.11	0.11	0.18
Cl	n.a.	n.a.	n.a.	0.07	0.07	0.04
SO_2	n.a.	n.a.	n.a.	0.04	0.01	0.04
Total	100.18	100.17	99.95	99.99	99.70	100.29

	Melt Inclusions			Groundmass		
Sample no.	C-3 Fsp2-MI2	C-20 Fsp1-MI5	C-19 Fsp1-MI5	C-73 GM-ud1	C-101 GM-ud4	C-89 GM-ud1
SiO_2	56.39	60.93	62.55	73.10	70.19	67.12
TiO_2	1.35	0.59	0.59	0.61	0.46	0.20
Al_2O_3	15.07	15.13	16.26	13.15	14.64	19.71
FeO	6.03	4.28	3.51	2.45	2.40	1.33
MnO	0.36	0.26	0.26	0.15	0.11	0.13
MgO	2.47	1.46	1.19	0.43	0.73	0.43
CaO	4.09	4.06	3.23	0.58	0.94	3.04
Na_2O	6.77	6.80	6.89	3.49	4.21	3.87
K_2O	4.87	4.84	4.97	5.80	5.73	3.69
P_2O_5	0.76	0.39	0.33	0.08	0.11	0.08
F	0.07	0.07	0.00	0.10	0.08	0.08
Cl	0.71	0.74	0.53	0.25	0.15	0.07
SO_2	0.04	0.04	0.09	0.04	0.06	0.03
Total	98.97	99.58	100.41	100.23	99.80	99.79

Blocks in the pyroclastic block flows collided with each other and the ground surface during transport. Such collisions endured for up to 0.01 s (assuming a speed of 30 m/s for the blocks, as deduced from video records of the 1998 Merapi eruption, and a maximum length of an observed impact mark of 0.3 m). In this short time, crushing, deformation and remelting took place, as shown by foliated cataclasite, rotated lithic clasts within the cataclasite, and striations on the pseudotachylite surface. The smooth appearance of striations reveals simultaneous deformation and melting. Maximum strain rate occurred on the very margin of the blocks, as proved by a decrease in grain-size from the cataclasite towards the pseudotachylite glass skin at the slip face. Assuming v=30 m/s as velocity of the blocks and L=6 mm as thickness for the deformation zone, the strain rate S can be estimated as

$$S = v/L + S' \quad (1)$$

with S′ being the strain rate which can be absorbed by the rock without any change in texture. Following Spray (1995), S′ is $<10^{-2}$ s^{-1} for granite which is negligibly small compared with $v/L=5\times10^3$ s^{-1} in our case. We can thus estimate a maximum strain rate of 5×10^3 s^{-1} in the deformation zone on the very margin of the blocks. From the relationship of comminution, melting, strain rate and resulting deformation rock types from Spray (1995), a combined occurrence of cataclasite and pseudotachylite due to progressive comminution is most likely in Merapi block-and-ash flows. However, an exact mass balance of cataclasite and pseudotachylite is virtually impossible due to the fact that much of the melt was probably lost to the advancing pyroclastic flow.

Plausibility of melting induced by block impact

To test the plausibility of impact-induced melting to occur, two points should be considered. Firstly, experiments by Spray (1995) showed that a critical strain rate of 10^2 s^{-1} is required. Given a 6-mm-thick deformation zone, a critical velocity of 0.5 m/s is sufficient to induce melting. Thus, block velocities could vary over a rather wide range – which is most likely the case in the complex system of a pyroclastic flow – and would still be higher than the required critical value.

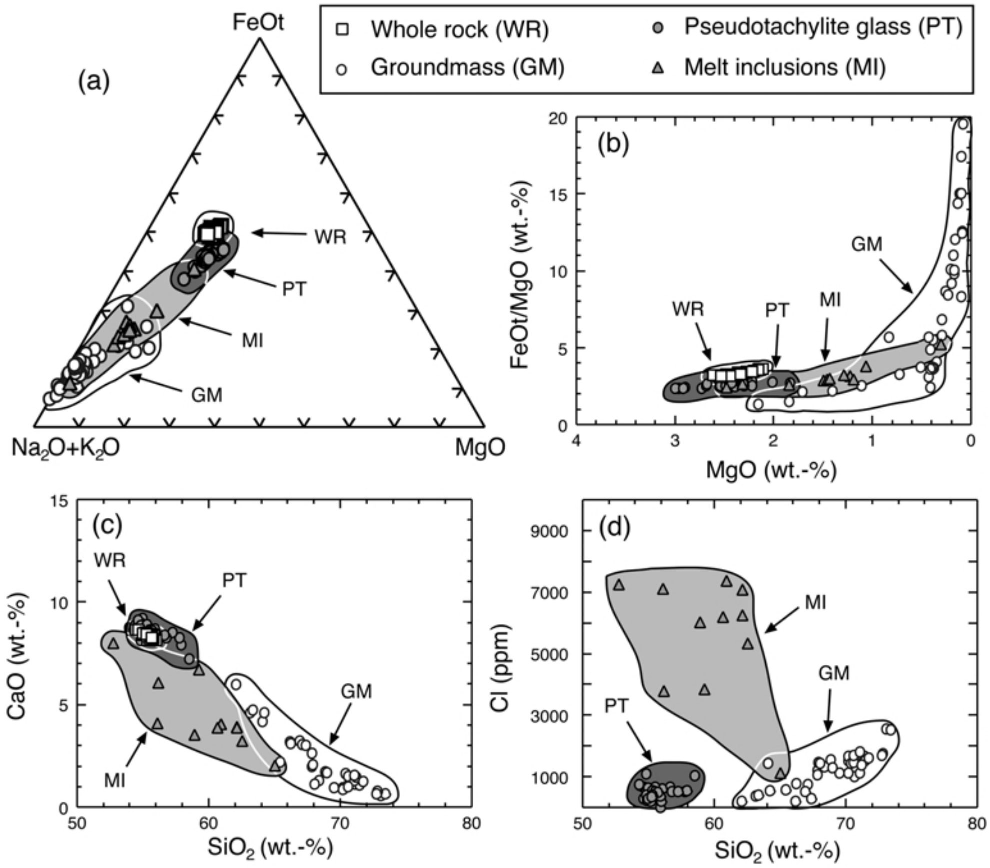


Fig. 4 **a** AFM-plot of whole rock of the 1998 eruption (plotted as *filled squares*), groundmass (*open circles*), melt inclusion in plagioclase (*filled triangles*) and pseudotachylite glass (*filled circles*). Note field of pseudotachylite glass overlapping the fields of whole rocks and primitive melt inclusions. This is indicative of the pseudotachylite glass being a bulk melt of the whole rock rather than a squeezed-out residual liquid represented by the groundmass compositions. **b** FeO/MgO vs. MgO also shows overlapping fields of whole rock, pseudotachylite, primitive melt inclusion and the least evolved groundmass compositions. Highly evolved groundmass plots towards high FeO/MgO-ratios with little MgO-content and differs greatly from pseudotachylite compositions (*symbols* as above). **c** CaO vs. SiO_2 defines chemical fields for the four compositions with overlapping fields for whole rocks, primitive melt inclusions and pseudotachylite. Pseudotachylite and residual groundmass do not overlap, allowing clear distinction of both (*symbols* as above). **d** Cl-content (in ppm) measured by EMP vs. SiO_2. Primitive melt inclusions show highest Cl-content, reaching up to 7,400 ppm, whereas evolved groundmass spans a range from 200 to 2,500 ppm. This contrasts the Cl-content of pseudotachylite ranging from 0 to 1,100 ppm with no overlap in SiO_2 for groundmass and pseudotachylite glass. Severe degassing of the pseudotachylite glass during impact and bulk remelting is therefore suggested (*symbols* as above)

Secondly, temperature increase at the surface of blocks must be high enough to allow melting of the bulk rock. The largest observed glassy pseudotachylite (0.3×0.06×0.0001 m in size) has a volume of 1.8×10^{-6} m^3. With a density of 2,000 kg/m^3, its mass m_{IM} amounts 3.6×10^{-3} kg. We infer a temperature increase of ΔT=1,000 °C to be needed for complete remelting. The required energy E_{Impact} must be subtracted from the kinetic energy E_{Kin} of a block. According to

$$E_{Impact} = cp \times m_{IM} \times \Delta T \quad (2)$$

with a specific heat capacity cp=1,350 J/kg K (Robertson 1988), the required energy amounts 4,860 J. The kinetic energy of a block

$$E_{Kin} = 0.5 \times m_{Bl} \times v^2 \quad (3)$$

with a volume of 1 m^3 (the minimum volume of an impact mark-bearing block), a density of 2,000 kg/m^3 and a velocity of 30 m/s amounts to 900,000 J. According to

$$E_{Impact} = 0.5 \times m_{Bl} \times \Delta v^2 \quad (4)$$

the subtraction of E_{Impact}=4,860 J causes only a slight decrease in block velocity of Δv=2.2 m/s. Thus, this block could deliver the energy required for impact melting at least ten times prior to halt. This rough calculation shows the feasibility of impact melting associated with an increase in temperature of some 1,000 °C by the impact of a meter-sized block. Such a block could experience several impact melting collisions without major effect on its velocity. A temperature increase of 1,000 °C may lead to a melt temperature of 1,300 °C at the block surface, assuming an initial temperature of ca. 300 °C of the block, an estimate consistent with reports on the 1984 deposits at Merapi (Boudon et. al. 1993). A temperature of 1,300 °C is well above the liquidus of 1,240 °C for recent Merapi andesitic melts (Murase and McBirney 1973).

Higher initial block temperatures of 550 °C as estimated for the 1994 Merapi block-and-ash flows (Voight and Davis 2000) or 600 °C for the June 1980 Mount St. Helens pyroclastic flows (Banks and Hoblitt 1996) would furthermore increase the probability of pseudotachylite generation. Thus, melt generation due to block impact is easily accomplished in block-and-ash flows such as at Merapi volcano.

Implications for transport mechanisms

The occurrence and random distribution of collision-related pseudotachylite on block surfaces imply that blocks have been transported by chaotic rotation, saltation and tumbling. The random orientation of the impact marks supports the notion of granular flow mechanism rather than any other currently discussed flow mechanism. In addition, the chaotic orientation of striations leads us to infer that momentum transfer has been dominated by short-lived intergranular collisions, and that the blocks have been transported in the collisional regime of a grain flow rather than in a pure frictional regime, where blocks should exhibit marks with parallel, not randomly orientated, striations.

Conclusions

- Pseudotachylites on surfaces of blocks in block-and-ash flow deposits have been generated by frictional melting of bulk rock due to impact-induced high-velocity slip.
- This type of pseudotachylite on volcanic blocks represents a new group of pseudotachylite.
- The maximum strain rate in the deformation zone can be estimated as $5\times10^3\ s^{-1}$.
- The occurrence and distribution of impact marks indicate that blocks have been generally transported by chaotic rotation, saltation and tumbling.
- The random orientation of the impact marks allows us to infer grain flow as the major transport mechanism, in particular within the collisional regime as indicated by chaotic orientation of striations.

Note added in proof While this paper was in review, Grunewald et al. published *Friction marks on blocks from pyroclastic flows at the Soufriere Hills volcano, Montserrat: Implications for flow mechanisms* (Grunewald et al. 2000.

The observations and interpretations of these authors are very similar to ours, especially with respect to flow mechanisms. However, there are two major differences.

Firstly, our more-detailed study of volatiles in the Merapi pseudotachylites, melt inclusions and groundmass clearly indicates effective degassing during formation of pseudotachylite. Our work circumstantiates this effective degassing with detailed EMP-derived Cl-contents of pseudotachylites, melt inclusions and groundmass.

Secondly, Grunewald et al. interpret the Soufriere Hills pseudotachylite as having been generated by flash melting of the pyroclastic flow matrix trapped between shearing large blocks, rather than melting of the blocks themselves. Our results, comprising a more extensive data set, clearly indicate bulk melting of the blocks on impact instead. Moreover, a gradual decrease in grain-size within the cataclasite towards the glassy pseudotachylite, also observed in Soufriere Hills marks, shows that deformation rates were at a maximum at the very outer layer. If the Grunewald et al. model of matrix agglutination were correct, an increase in grain-size towards the outer margin of the marks would be expected, and, according to their views, the highest strain rates should occur on the interface between the block and the agglutinating particles from the flow matrix. This should theoretically produce a decrease in grain-sizes from the block to the pseudotachylite, followed by an increase in grain-size towards the outer mark surface. Such textures were neither observed in marks from Soufriere Hills (Grunewald et al. 2000) nor from Merapi.

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