A model for frictional melt production beneath large rock avalanches

Fabio Vittorio De Blasio¹,² and Anders Elverhøi¹,²

Received 8 July 2007; revised 6 December 2007; accepted 22 February 2008; published 7 May 2008.

Two puzzling traits of giant rock avalanches (sturzstroms) are the decrease of the effective friction coefficient as a function of the volume (volume effect) and the remarkable preservation of large geological structures during the flow, demonstrating that the upper cap of a sturzstrom travels coherently on top of a basal shear layer. Hence, frictional heat is rapidly produced along the shear layer, which could explain the formation of sheets of molten rock inside certain landslide deposits. It has been conjectured that a molten layer could potentially self-lubricate the base of the sturzstrom. To theoretically investigate this scenario, we consider the model of a rock slab sliding on an inclined surface. We present a set of coupled differential equations to calculate the frictional heat produced, the properties of the molten layer (thickness, temperature, and velocity distribution), and the motion of the slab. Our simulations illustrate the onset of self-lubrication and show the volume effect when the melt viscosity is low, corresponding to a simulated mafic composition of the rock. For a felsic composition (and to some extent also for intermediate melts) we find that the melting introduces more resistance at the beginning of the melting process, in close similarity with frictional melting in tectonic faults. However, in contrast to faults, the rock avalanche is capable of overcoming the initial resistance in at least two situations: if the rock is rigid and the landslide is sufficiently thick or else if the material of the landslide is disintegrated. The simulations also show that although self-lubrication is a viable possibility to explain the runout of sturzstroms, there are rather stringent conditions for the formation of a molten layer of good lubricating qualities. More generally, we suggest that the properties of the Coulomb frictional law at the interfaces may change radically during sliding and that the assumption of constant friction does not represent a good model in landslide calculations.


1. Introduction

The riddle of the anomalous runout of giant landslides (sturzstroms) has attracted the attention of researchers since Heim’s pioneering analysis [Heim, 1932; Scheidegger, 1973; Hsu, 1975]. The problem arises from the decrease of the apparent frictional angle $\phi$ as a function of the landslide volume $V$, where $\tan \phi = H/R$ is the ratio of the fall height in the gravity field $H$ and the runout $R$. Despite the dispersion, data can be reasonably fitted by a power law [Scheidegger, 1973]

$$\tan \phi = a V^\gamma,$$

where $a$, $\gamma$ are empirical constants and $\gamma \approx -0.15 < 0$. This law agrees with the common observation that the deposits of small landslides (say 100,000 m³ in volume) typically rest at the toe of the main gradient located at 30–40 degrees, whereas giant landslides of volume >10⁹ m³ are capable of traveling up to 10 times the fall height, even progressing against slope. In practice, equation (1) implies that the runout of rock avalanches increases more rapidly with the volume than the fall height does.

Numerous suggestions have been put forward to explain relation (1). It has been noticed that the practice of measuring runout and fall height from the front point of the landslide rather than from the center of mass adds a bias to the data [Straub, 2001]. The effect, however, persists also when data refer to the center of mass, albeit with different empirical constants. Mechanisms based on air lubrication were suggested by Kent [1966] and Shreve [1968], though it is known nowadays that lunar and Martian landslides, where gas density is insignificant, also exhibit anomalously long runout [Howard, 1973; Lucchitta, 1979; McEwen, 1989]. Other researchers have suggested that the mobility may be enhanced without invoking exotic mechanisms if grains are in a state of vigorous agitation [Davies, 1982].
This is partly confirmed by numerical simulations based on molecular dynamics algorithms of rock avalanches where grain-grain collisions are calculated explicitly [Campbell, 1989, 1990]. Results show a volume effect [Campbell et al., 1995], even though Calvetti et al. [2000] came to opposite conclusions on the basis of a similar technique. Other mechanisms for enhanced runout invoke acoustic fluidization due to high-frequency acoustic waves traveling through the granular medium [Melosh, 1979], vaporized pore water [Habib, 1975; Goguel, 1978], dispersive forces exerted by powder-sized grains [Hsü, 1975], the energetic disintegration of the avalanche [Davies and McSaveney, 1999], or the presence of water [Legros, 2002], whereas Dade and Huppert [1998] explained long-runout rock avalanches assuming a yield stress rheology for the disintegrated rock.

[4] One key observation concerning giant rock avalanche deposits is that despite the intense comminution, macroscopic features such as dikes and secondary mineralized veins in the deposit have remained in relative position as they were before the landslip. In this respect, two examples from the Alps are frequently reported: the calcite veins in the calcarious landslide in Flims (Switzerland) and the diabase dikes in the metamorphic landslide of Koefels in Austria [see Erismann and Abele, 2001]. A large dike in the deposits of the Koefels landslide is shown in Figures 1a and 1b, appearing as the dark shadow against the whitish material. At closer examination the material appears to be completely disintegrated and has the consistency of agglutinated powder. This demonstrates that the outer cap of a sturzstrom (also called the plug layer hereafter) may be capable of traveling unmixed on top of a relatively thin region (termed the shear layer) where the shear rate must become very large to account for the high velocity of the sturzstrom. The plug-like motion of a landslide is also indicated by the common, but not general, observation of jigsaw clasts abandoned on some landslide deposits (“jigsaw effect” according to Shreve [1968]). Note, however, that the presence of gaps between jigsaw clasts sometimes indicates a residual shear deformation after clast breakage (M. McSaveney, private communication, 2007). The deposit appearance is often more intricate especially for thicker landslides; for the calcareous Flims landslide [Pollet and Schneider, 2004] there are actually multiple shear zones. The presence of large portions without relative dislocation, however, always indicates conditions of intense shear at the boundaries.

Figure 1. The Koefels landslide deposits in Austria. (a) A diabase dike was displaced some kilometers without losing its essential outline, which implies a plug-like transport. (b) A closer view of the Koefels deposits reveals that the original gneissic rock has been finely crushed. (c) A sample of frictionite (right) compared to the original rock (left). (d) Another frictionite sample from the Koefels landslide.
Table 1. Salient Frictionite Data

<table>
<thead>
<tr>
<th>Location</th>
<th>Koefels</th>
<th>Langtang</th>
<th>Arequipa</th>
<th>Taiwan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date or age</td>
<td>Tyrol, Austria</td>
<td>Himalaya, Nepal</td>
<td>Peru</td>
<td>Taiwan</td>
</tr>
<tr>
<td>Volume, km³</td>
<td>≈8700 ¹⁴C years B.P.</td>
<td>25–30 ka</td>
<td>younger than 2.42 Ma</td>
<td>1999</td>
</tr>
<tr>
<td>Original rock</td>
<td>gneiss</td>
<td>mostly gneiss, also migmatites and granite</td>
<td>andesite</td>
<td>sedimentary</td>
</tr>
<tr>
<td>Maximum thickness</td>
<td>500</td>
<td>300</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>of the landslide, m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kind of frictionite</td>
<td>glassy in the deep layers, and more vesicular in the shallow</td>
<td>glassy</td>
<td>glassy; exhibits striations on the top of the layer</td>
<td>both glassy and vesicular; exhibits striations, interspersed microclasts, filled cracks and flux structures</td>
</tr>
<tr>
<td>Maximum thickness</td>
<td>variable, usually a few cm thick, up to some decimeters according to Sørensen and Bauer [2003]</td>
<td>20</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>of frictionite layer, mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H/R (approximate value)</td>
<td>0.2</td>
<td>unknown</td>
<td>0.1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

[5] A first possible depiction of the shear layer is that of a mass of agitated grains maintaining the plug layer aloft by repeated bounces. However, it is possible to show that an ensemble of bouncing rock grains is incapable of supporting a rocky slab for realistic values of the coefficient of restitution and at the low sloping angles characteristic of sturzstroms (see Appendix A for a simple analytic calculation). Thus, the plug layer must be traveling in contact with its base, where the high shear rates will generate frictional heat. On the basis of observations especially from Koefels, Erismann [1979, 1985] has suggested that the heat produced can potentially melt the interface and lubricate the landslide. Because the frictional heat increases with overburden pressure, this could also explain equation (1). Evidence for frictional melting within landslides, however, is uncommon. Thin rare layers of fused rock (frictionite) reported independently in the literature have been interpreted as the result of the frictional heat along a shearing plane that does not necessarily coincide with the base of the landslide. To our knowledge, the best documented cases of landslide frictionites are the Koefels landslide in Austria shown in Figures 1c and 1d [Erismann, 1979; Erismann and Abele, 2001], Arequipa in Peru [Legros et al., 2000], Langtang in the Himalayas [Masch et al., 1985], and a recent case in Taiwan [Lin et al., 2001].

[6] Table 1 gathers the salient data for these four sites. The picture that emerges from these scarce but significant data is that frictionite is usually arranged in thin layers (a few centimeters thick). No such layer could form if a landslide spread as an irregular ensemble of falling grains, nor if the shear layer were significantly thick, because the heat would be dissipated on a larger volume and the rocks would not melt. Thus, it can be suggested that the shear layer consists of a thin sliding surface where frictional heat is generated; the existence of frictionite sheets shows that in some cases this heat is capable of melting the rock. Table 1 also shows that different rock types are involved (but not carbonates, which do not fuse upon friction) and that both glassy and vesicular textures occur.

[7] It is interesting that frictional melting may also occur along the outline of faults in tectonically active and catastrophic zones, albeit quite rarely. Molten rocks generated by friction (preferably called pseudotachylytes rather than frictionites by structural geologists and petrologists) are intensively studied in relation to earthquake triggering mechanisms [see, e.g., Magloughlin and Spray, 1992]. Rocks are known to fracture and then to melt rapidly in rotary apparatuses, simulating friction at high pressure [see, e.g., Tsutsumi and Shimamoto, 1997; Spray, 2005]. Thus it is clear that the accumulated information on the physics and geochemistry of rock melting in fault zones may be valuable also in understanding the generation of molten rocks underneath landslides.

[8] Some researchers have estimated the heat produced at the sole of landslides and the amount of rock melting [Erismann, 1979; Sørensen and Bauer, 2003], as well as the ensuing lubrication effect [Erismann, 1979]. However, to our knowledge, no self-consistent calculations have been proposed where the landslide progression downslope is coupled with the equations for heat flow perpendicular to the interface. Moreover, the conditions for the formation of a frictionite layer have been scarcely addressed. In the present paper we suggest a model for calculating the heating generated at the sole of a landslide and the generation of melt. The model accounts for the modification of the equations of motion due to the molten layer, which in turn affects energy dissipation.

2. A Slab Model for Self-Induced Lubrication of Rocky Joints Driven by Gravity

[9] In the following we consider a simple model of frictional melt generation at the interface between two sliding rocky surfaces. The model consists of a rigid slab driven by gravity and sliding on top of an inert surface. For simplicity, we start considering the slab and the inert surface as nondisintegrated units; in considering the applications we will discuss in a second step the role of granularity of a rock avalanche. At the beginning of a simulated slide event, the frictional heat is produced by the Coulomb friction between the two parts. When the local temperature reaches the melting point, the newly produced melt modifies the total shear resistance at the joint. Models of rock melting have been very recently suggested in relation to faults and earthquakes dynamics [see, e.g., Fialko and Khazan, 2005; Rempel and Rice, 2006; Sirono et al., 2006]. In the
case of rock avalanches, the relative movement is self-controlled by gravity rather than external tectonic forces. Thus, the dynamics are determined by a set of time-dependent differential equations coupling the equation of motion for the lubricated rocky slab above the failure plane and the thermomechanics of melt production and heat flow.

[10] Without melt generation the shear resistance $\tau$ is purely Coulomb frictional, $\tau = \rho g H \cos \beta \tan \phi$, where $\rho$, $g$, $H$, $\beta$, and $\phi$ are the density, the gravity acceleration, the landslide height, the slope angle, and the friction angle, respectively. The presence of a thin layer of lubricating melt introduces in the resistance a term of the form $\tau \approx \kappa \mu U / \delta$, where $\mu$ is the viscosity, $\delta$ is the thickness of the molten layer, $U$ is the velocity, and $\kappa$ is a constant. The viscous shear stress prevails over the Coulomb resistance whenever $\delta$ becomes larger than a characteristic thickness $\lambda$ representing the ruggedness of rock asperities at the interface. We define $f$ as a parameter quantifying the effect of the lubricating layer in the reduction of Coulomb friction in such a way that $f = 1$ when Coulomb friction dominates the shear resistance and $f = 0$ for purely viscous stress. We made two possible choices for the behavior of $f$ as a function of $\delta$ and $\lambda$ when $f = 1$. In the “sharp model” for the solid-liquid interface, $f = 1$ if $\delta < \lambda$ and $f = 1$ if $\delta > \lambda$; in other words, we start from a purely frictional dissipation switching to viscous when the thickness of the molten layer becomes larger than $\lambda$. In the “smooth model” we take $f = 1$ if $\delta < \lambda$, whereas for $\delta \geq \lambda$ we impose an exponential decrement of Coulomb friction with height $f = 1 - \exp[-|\delta - \lambda|]$, corresponding to the statistical decrease of the contact area [Rabinowicz, 1995]. When Coulomb friction is the only force acting on the slab, the total force (including gravity) is

$$F = Mg \sin \beta \left[ 1 - \frac{\tan \phi}{\tan \beta} \operatorname{sgn}(U) \right],$$

where $\operatorname{sgn}(U)$ is the sign of the velocity. On the other hand, if only viscous resistance takes place, the total force becomes $F = Mg \sin \beta - \kappa S \tau_{\text{visc}}$, where

$$\tau_{\text{visc}} = U \left[ \int_0^\delta \frac{dy}{\mu(y)} \right]^{-1}$$

is the viscous stress, $U$ is the slide velocity, and $\phi$ is the friction angle of the material sliding on the bed. Note that in contrast to the gravity pull and to the Coulomb friction, the viscous term is the only force term that does not depend on the mass. Thus, a volume effect will arise naturally if part of the resistance is viscous rather than frictional. The equation of motion of the slab is based on a linear combination of Coulomb and viscous terms

$$\frac{dU}{dt} = g \sin \beta \left[ 1 - \frac{\tan \phi}{\tan \beta} \operatorname{sgn}(U) \right] - \left( 1 - f \right) \kappa \tau_{\text{visc}} \rho H.$$  

[11] The linear summation of frictional and viscous stresses can be justified considering the irregularity in the contact of the two surfaces. The rough indentations between the slab and the base experience a frictional stress, whereas the parts not directly in contact become hydrodynamically lubricated [Rabinowicz, 1995]. Hence, the parameter $f$ represents the fractional contact area of the two solid sliding surfaces. Note that whereas the Coulomb friction is assumed to occur only at the base of the slab ($y = 0$), the viscous dissipation takes place in the body of the molten layer, between $y > 0$ and $y = \delta$.

[12] Likewise, the energy is dissipated unevenly in the slab. The Coulomb friction produces an energy flux at the base of the slab; the viscous dissipation occurs in the whole molten layer. Defining the energy dissipated per unit time and unit area $J$, the Coulomb friction dissipation goes like $J \propto \tau U$, where $\tau$ is the frictional stress. More explicitly,

$$J = e \frac{dE}{dt} = e \rho g H \cos \beta \tan \phi U f,$$

where $e$ is a geometrical factor accounting for the fact that only a part of the produced heat dissipates locally and results in rock melting. We use the calculated value for $J$ as a Neumann boundary condition at the interface; namely, we impose that the temperature gradient satisfies

$$\left( \frac{\partial T}{\partial y} \right)_{y=0} = -\frac{J}{\chi},$$

where $\chi$ is the thermal conductivity and $y$ is the coordinate perpendicular to the interface between the slab and the ground ($y = 0$ at the interface). The viscous dissipation rate gives a term of the form $\mu(\partial u(y)/\partial y)^2$, where $u(y)$ is the velocity of the melt parallel to the slope path, and thus the temperature inside the molten layer underneath the landslide is calculated with the heat equation

$$\frac{\partial T}{\partial y} + \frac{\chi}{c} \frac{\partial^2 T}{\partial y^2} = e(1 - f) \frac{\mu(y)}{c} \left( \frac{\partial u}{\partial y} \right)^2,$$

where $c$ is the specific heat. As the simulation proceeds, we calculate $\delta$ as the level of the melting point, so that for $y < \delta$ the material is molten (latent heat is also accounted for in the calculations; this is the so-called Stefan problem [see, e.g., Turcotte and Schubert, 2001]). The viscosity of molten rock is calculated according the Arrhenius equation [Spera, 2000]

$$\mu = \mu_0 \exp \left( \frac{B}{T} \right),$$

where $T$ is the average temperature of the molten layer and $B$ and $\mu_0$ are constants characteristic of the melt. The coupled equations (2)–(6) are solved numerically in time considering $U$ as the velocity of the center of mass. A fine vertical mesh is utilized to calculate the heat flow properties as a function of the height $y$. The relevant physical quantities are collected in Table 2.

[13] In applying the model to real sturzstroms, the most important aspect not included is the presence of comminute rock underneath a landslide. We should add that melting cannot directly explain the long runout of landslides composed of carbonate rocks, as these rocks dissociate chemically and escape melting. A possibility is the increased
pressure of generated carbon dioxide [Erismann, 1979] or the generation of high-pressurized steam [Habib, 1975; Goguel, 1978; Vardoulakis, 2000; De Blasio, 2007]. Also, because landslides usually elongate during flow, the height of the landslide normally decreases with time. This will decrease the rate of energy injection per unit area, an effect that should also be included in a more complete calculation.

3. Results

3.1. Single-Slab Model

[14] Figure 2 shows the results of the simulations for a block initially 76 m high using the smooth model for the interface. Figure 2a shows the artificial landscape used in the calculations. The velocity of the center of mass (Figure 2b) reaches the value of about 55 m s\(^{-1}\), compatible with values of a fast slide. Much of the frictional heating is produced early: the temperature averaged over the heated layer (Figure 2c) reaches a high value of about 2000 K after 1 km of runout and decreases slightly afterward. The thickness of the molten layer (Figure 2d) is found to increase steadily, reaching a maximum value of about 8 mm. The decrease of the coefficient \( f \) from unity to small values (Figure 2e) indicates the passage from a flow dominated by Coulomb friction to one controlled by stress in the viscous layer. Finally, Figure 2f shows the ratio \( r \) between the actual shear resistance (due to both Coulomb and melt friction) and the friction if melting were absent. Notice that the molten layer actually increases the resistance at the beginning of the fusion process, as signaled by the first peak. The reason is that at the onset of melting, the temperature is still relatively low (and the rock has high viscosity) while the thickness is small, implying a large viscous resistance \( \frac{t}{\kappa \mu U/d} \) which sums up to the Coulomb friction. A similar increase in the resistance close to the melting point has been measured in experiments and is also reproduced by numerical models of fault lubrication [Rabinowicz, 1995; Spray, 2005; Fialko and Khazan, 2005; Rempel and Rice, 2006; Sirono et al., 2006].

[15] Varying the initial height of the landslide, we studied the model predictions regarding the volume effect. Figure 3 shows the apparent friction coefficient calculated as the.

---

**Table 2. Values Used in the Computer Simulation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (MKS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity ( \chi ), W m(^{-1}) K(^{-1})</td>
<td>3.5</td>
</tr>
<tr>
<td>Specific Heat ( C ), J kg(^{-1}) K(^{-1})</td>
<td>1000</td>
</tr>
<tr>
<td>Density ( \rho ), kg m(^{-3})</td>
<td>2700</td>
</tr>
<tr>
<td>Latent Heat, J kg(^{-1})</td>
<td>(3 \times 10^5)</td>
</tr>
<tr>
<td>Melting Temperature, K</td>
<td>1200</td>
</tr>
</tbody>
</table>

---

**Figure 2.** Results of the slab model. (a) The artificial sliding profile for the block, (b) the velocity of the block, (c) the average temperature of the molten layer (report of the average temperature close to the interface before melting takes place), (d) the thickness of the molten layer, (e) the thickness of the \( f \) parameter (see text), and (f) the ratio \( r \) between the actual shear resistance (due to both Coulomb and melt friction) and the friction if melting were absent. All the quantities are plotted as a function of the horizontal distance reached by the front of the simulated landslide. The parameters in the calculation are for a melt of intermediate composition [Spera, 2000]: \( \chi = 3.5 \text{ W m}^{-1} \text{ K}^{-1} \); \( \tan \phi = 0.3 \); \( \kappa = 1 \); \( \mu_0 = 3.9 \times 10^{-11} \text{ Pa s} \); \( B = 13,889.9 \text{ K} \); \( e = 0.3 \); \( \lambda = 0.5 \text{ cm} \).
ratio of the vertical to the horizontal displacement of the
slab, using the same slope profile as in the previous
example. When the initial height is less than a certain limit
(below about 20 m with the input parameters considered
here), the apparent friction coefficient is independent of
landslide height and equals the assigned static Coulomb
friction \( \tan \phi \). For thicker slabs, melting at the sole begins to
occur, and the friction coefficient changes accordingly.
Below a definite value of slab thickness (which depends
on the input parameters), the apparent friction coefficient
actually increases slightly, as evident from the bump in
Figure 3 labeled as “increase in friction resistance.” This
is because both the temperature and the thickness \( \delta \) of the
molten layer remain small so that the combined effect of
viscous and Coulomb resistance becomes relatively large, as
already discussed in relation to the peak in Figure 2e. Thus,
if the molten layer remains too thin, the ensuing increase in
the resistance makes the slab stop early. Beyond a critical
slab thickness, the additional resistance of the molten layer
is overcome by the effect of the gravity pull and inertia. As
the slab accelerates again, it produces more melt at high
temperature, which finally decreases the shear resistance.
As a consequence, the apparent friction coefficient decreases regularly, signaling the onset of a volume effect.
We found that when the initial thickness of the simulated
landslide has become 100 m, the apparent friction angle has
decreased to about 0.085. Assuming that the thickness of
landslides increases with their volume, the present results
indicate a volume effect like in the empirical relation (1).
Considering the uncertainties of the model, it would be
meaningless to calibrate the input parameters to fit the
correct exponent.

One of the most important parameters in the simu-
lation is the melt viscosity. The viscosity depends dramat-
ically on the composition of the original rock, on the
presence of a solid fraction in the melt, and also on water
content. For example, a tiny (3%) variation in water content
by 5 orders of magnitude [Spera, 2000]. We thus studied the
prediction of the model and especially the volume effect
with a change in the viscosity. Results are shown in Figures
4a and 4b with the sharp model and the smooth model for
the interface, respectively. With a mafic composition (which
has essentially the highest melting temperature and lowest
viscosity and is shown with circles in Figure 4) the volume
effect is greater than with intermediate (crosses) and felsic
dots) compositions, the other parameters being the same.
The decrease of the effective friction angle is also delayed to
greater thicknesses for the more felsic compositions. The
sharp model for the interface produces a more pronounced
volume effect. Note that with a smooth model the volume
effect does not appear at all for felsic composition with
these parameter values. We emphasize that the properties of
real rocks in proximity of the melting point is complex, as
the different component minerals melt at different temper-
atures. Here we maintain a simplified view where a certain
rock composition has a fixed melting point. Likewise, no
attempt is made to account for the modification of the rock
properties due to the water phase likely present in the body
of many landslides.

3.2. Two-Slab Model

[17] We have shown earlier that for felsic and interme-
diate compositions the melt initially delays the block, like in
melting along fault surfaces. However, there is an essential
difference between the cases of faults and landslides.
Sufficiently far from the shearing zone, the rock along the
fault is intact, whereas in a landslide the original rock is
probably disintegrated to a granular medium. Hence, as a
consequence of the increased resistance at the viscous layer,
the landslide body will likely fail at a different level with
lesser sliding resistance. We have thus considered a vari-
ation of the basic model (a two-slab model) as follows. The
calculation is started as in the previous case. When the
parameter \( r \) becomes larger than unity, a new shearing zone
opens up at a height \( H_1 \) from the base and the slab splits in
two subunits (see Figure 5). The lower slab, which is
sandwiched between the upper slab and the base, is coupled
 frictionally viscously with the upper slab with equations
similar to equation (2). The equations of motion of the
system can be written as

\[
\frac{dU_{CM}}{dt} = g \left[ \sin \beta - \cos \beta \tan \phi \text{sgn}(U_1) \right] - (1 - f) \kappa \frac{\tau_{visc}}{\mu H_1},
\]

\[ (7a) \]

\[
\frac{dU_2}{dt} = g \left[ \sin \beta - \cos \beta \tan \phi f_2 \text{sgn}(U_2 - U_1) \right] - (1 - f_2) \kappa \frac{(U_2 - U_1)}{\mu(H - H_1)} \int_0^y \frac{dy}{\mu(y)},
\]

\[ (7b) \]

\[
\frac{dU_1}{dt} = \frac{H}{H_1} \frac{dU_{CM}}{dt} - \left( \frac{H}{H_1} - 1 \right) \frac{dU_2}{dt}.
\]

\[ (7c) \]
where the labels “1” and “2” denote the lower and upper slabs, respectively, and “CM” refers to the center of mass of the two slabs. Melt may also form at the secondary interface, requiring the last term in equation (7b), where $d_2$ is the thickness of the molten layer at the second interface and $f_2$ is calculated accordingly like for the primary interface.

Figure 6 shows the velocity as a function of time for the lower slab and for the center of mass. At the onset of melting, the slab splits and the lower slab strongly decelerates; the viscous friction at the base diminishes as the velocity at the base decreases, until the friction between the upper and the lower slab prevails. The lower slab then accelerates again; the heat at the boundary between the lower slab and the base has diffused and increased the thickness of the molten layer, with a consequent diminution of the viscous stress. When the lower and the upper slabs proceed at the same velocity, the two slabs are assumed to weld. Figure 7 shows a possible sequence of events in a real rock avalanche suggested by the calculations of Figure 4. The progression may lead to the formation of multiple layers of frictionite.

Figure 8 shows the relationship between the apparent friction angle and the slab thickness obtained with different compositions. Results are obtained with (a) a sharp model and (b) a smooth model for the interface. Circles, mafic composition; crosses, intermediate composition; dots, felsic composition. For all the simulations it is assumed that $\lambda = 1$ mm. For the felsic and mafic compositions the viscosity parameters and temperatures are as follows: $\mu_0$ (felsic) = $3.9 \times 10^{-8}$ Pa s; $\mu_0$ (mafic) = $3.9 \times 10^{-13}$ Pa s and the melting temperatures are $T_m$ (felsic) = 1000 K; $T_m$ (mafic) = 1400 K.

Figure 4. The calculated relationship between the apparent friction angle and the slab thickness obtained with different compositions. Results are obtained with (a) a sharp model and (b) a smooth model for the interface. Circles, mafic composition; crosses, intermediate composition; dots, felsic composition. For all the simulations it is assumed that $\lambda = 1$ mm. For the felsic and mafic compositions the viscosity parameters and temperatures are as follows: $\mu_0$ (felsic) = $3.9 \times 10^{-8}$ Pa s; $\mu_0$ (mafic) = $3.9 \times 10^{-13}$ Pa s and the melting temperatures are $T_m$ (felsic) = 1000 K; $T_m$ (mafic) = 1400 K.

Figure 5. The double-slab model. When the resistance at the sole becomes larger than the Coulomb friction resistance ($r > 1$), the center of mass slows down, but the slab must cut at another height $D_1$, where the resistance is lower. To simulate the split of the landslide body, the equations of motion are solved independently for the two slabs starting from the time when $r > 1$. 
slides and the large dispersion of the data with which equation (1) is built, the results appear to be satisfactory, without excluding other mechanisms of long runout.

4. Discussion

4.1. Temperatures

The present simulations indicate the development of high temperatures at the sliding plane, even though this conclusion critically depends on the input parameters of the simulation. Experiments in metal physics [Rabinowicz, 1995] show that the temperature may be strongly enhanced in small protruding junctions (flash temperature). This may cause melting in advance of the rest of the material. In analogy with metals [Rabinowicz, 1995; Persson, 2000], one can speculate that the behavior of frictional resistance of rocks with changing conditions such as temperature, pressure, or previous history is rather complex, even when we restrict ourselves to shear rates lower than those of interest during landslide movement. Previous investigators have shown ample variability of the friction coefficient with external conditions [see, e.g., Scholz, 2002; Tsutsumi and Shimamoto, 1997; Spray, 2005], demonstrating that it is not justified to assume a constant friction coefficient in proximity of the melting point. For example, Tsutsumi and Shimamoto report variations of the order of 60% in experiments with gabbro at different normal stresses (1.5–5 MPa) and slip rates (a few millimeters per second up to approximately meters per second) characteristic of fault displacement during earthquakes [Tsutsumi and Shimamoto, 1997]. Comparable changes were found by Spray [2005] with felsic composition (granite). Typically in these experiments the friction coefficient increases at the onset of melting and decreases when lubrication sets in. We note incidentally that the friction coefficient may be variable even when melting does not take place as found recently by Di Toro et al. [2004], who attributed the decrease of measured friction in quartz to the formation of a gel layer.

Moreover, high flash temperatures may be expected for clasts supporting the whole landslide and probably forming preferred pathways for stress and friction, as well as high basal load (1–10 MPa or more) potentially implies high flash temperatures exceeding the melting point.

4.2. Granular Effects

The present model addresses the case where the rock at the base of the slab melts instantaneously; the model parallels the kind of frictional melting occurring along a fault. However, in the case of fault displacement, a kind of intensely comminuted rock (a gouge comprising grains few
tens of micrometers across) is produced in addition or prior to melt [Wenk, 1978; Spray, 1995]; it is these gouge particles that melt upon high shear rates. Hence, the approximation adopted here is valid if the gouge particles melt rapidly in comparison to the sliding time of the slab.

One further complication is that in contrast to a fault displacement, the process of melting underneath a rock avalanche is likely to take place within a sheared granular bed. Accounting for the granular nature of the rock avalanche was the basis of the two-slab model. The difference between a gouge and a granular bed is that the gouge is produced by shearing and is characterized by very small grains. The granular bed is a consequence of the disintegration processes of the rock avalanche, which in principle results in a much wider distribution of grain sizes [Crosta et al., 2007]. Shear test experiments and numerical DEM simulations show that in a sheared granular bed the failure occurs more or less in a plane of thickness of the order of few grain sizes [see, e.g., Oda and Iwashita, 2000; Huhn et al., 2006]. Thus, melting will involve a plane of growing thickness like in the present model, rather than being distributed within a thick granular layer.

The presence of a granular medium may also cause the molten rock to percolate the granular material and wane in thickness. Conversely, field data show that frictionite occurs in rather neat layers, demonstrating that melt percolation in the granular medium must have been negligible during the flow [Erismann and Abele, 2001]. A partial explanation for this is provided by the recent measurements of Crosta et al. [2007] of the size spectra of grains in the Val Pola landslide. At a depth of about 70 m, comparable to the slab thickness adopted in the present calculations of Figure 1, the hydraulic conductivity of the fine-sized granular medium is about \( u \approx 10^{-6} \text{ m s}^{-1} \). The conductivity \( u \) is proportional to the permeability (which is an intrinsic property of the granular material) and is inversely proportional to the viscosity, and so the melt conductivity in the granular medium is of the order \( u \approx 10^{-11} \mu (\text{Pa s}) \text{ m s}^{-1} \). Calculated values are very low for basalt (\( u \ll 10^{-10} \text{ m s}^{-1} \)) and extremely small for rhyolite, \( u \approx 10^{-16} \text{ m s}^{-1} \). We suggest that the small value of the permeability results in a negligible effect of molten rock seepage in the granular medium.

If rock melting occurs at the sole of landslides, we face the problem of explaining the rarity of frictionites. A first observation is that only some types of rock will melt upon friction. Still, the documented cases should be more numerous even excluding the landslides lacking appropriate composition. Interestingly, frictionite also occurs rarely in faults joints, where it usually affects no more than a few meters along the joint: very little, considering that large faults may reach several kilometers in length [Scholz, 2002]. Can the analogy with fault frictionite be applied to explain frictionite rarity at the landslide soles? The rarity of fault frictionite is probably due to the high viscosity of melt at the onset of melting [Scholz, 2002] that causes a rapid damping of the displacement rate. A similar effect has been illustrated by our simulations (Figure 4). However, in contrast to faults, the simulated landslide was capable of overcoming the increased hindrance and finally to generate a more

Figure 8. Behavior of the \( H/R \) ratio as a function of the slab thickness: comparison of the single-slab model (crosses) and the two-slab model (dots). (a) Intermediate composition. (b) Felsic composition. Smooth model with \( \lambda = 3 \text{ mm} \).
effective lubricating layer. In the case of the single-slab model, valid for a rigid landslide, the inertia of the landslide mass and the constant effect of gravity were capable of winning the initial resistance but only if the landslide was sufficiently thick. In the two-slab model, valid for a disintegrated landslide mass, the resistance determined a transfer of the sliding plane, with the primary plane remaining active. Hence, in the simulations the melt determined a stoppage of the mass for thin, felsic (and to some extent intermediate) compositions and rigid landslide masses. 

[26] On the basis of these results, it is suggested that the generation of frictionite may be more continuous along landslide soles than in tectonic faults. We suggest that the reason for the notable difference between two cases is that velocities and displacements are much greater for landslides than for faults. Hence, the paucity of frictionite at the sole of rock avalanches requires a different explanation.

[27] In contrast to faults, landslide deposits are usually recognized on surface morphology; rarely is the basal surface exposed. The deposits are likely to entirely blanket the lowest strata including the molten layer, if present [Erismann and Abele, 2001]. Buried under several tens of meters of chaotic deposits, a thin frictionite layer will seldom be detected. Scrutinizing the profiles of recent landslide deposits longitudinally along the path, one may notice that the only portion of the slope path devoid of postevent deposits is usually the small segment between the scarp and the beginning of the deposits. (This is very evident for example in the Val Pola landslide deposit [Erismann and Abele, 2001].) However, our simulations show that the production of frictionite reaches the maximum level (about only 1 cm in thickness) at least some hundreds of meters from the scarp. This is because (1) the velocity at the beginning of the sliding is too low, (2) there has been little time for a thick frictionite layer to form, and (3) the cosine factor is smaller at the beginning where slope angles are greater, and so the basal pressure is reduced. Thus, frictionite is probably scarcely produced in the locations near the scarp. If we add that these locations are sometimes steep and difficult to inspect, considering the possible occurrence of a veneer of pulverized dust and the effect of precipitation [Erismann and Abele, 2001], then the difficulty in detection of frictionite is probably not surprising. The frictionite of Koefels shown in Figure 1c does derive from the proximal part of the landslide, but according to the reconstruction by Erismann [1979] and Erismann and Abele [2001] this location was well below the assumed landslide crest and must have been subjected to the passage of more than 1 km of horizontal movement of the landslide material. Clearly, this is a critical point for the theories of melt self-lubrication, and future field investigations should be undertaken to locate more frictionite locations, if any. Interestingly, it also appears that some snow avalanches develop an ice layer at their sole, probably due to melting of snow subjected to high shear rates (D. Issler, private communication, 2006), an example of which is shown in Figure 9. We notice that the lubricating model may also explain the occurrence of a volume effect on celestial bodies. It is observed that the apparent friction coefficient for landslides of the same height is higher on Mars than on Earth [see, e.g., McEwen, 1989; Dade and Huppert, 1998]. This can be understood in the present framework by invoking a diminished melt production as a result of the reduced gravity field.

5. Conclusions

[28] By using a time-dependent model we studied the motion of a landslide modeled as a rigid slab subjected to melt generation and self-lubrication at the base. We found that the friction produces a strong increase of the temperature, and we modeled the generation of a molten layer at the interface and the modification of the equation of motion of the rock avalanche. Depending on the rock composition and water content, we found that melting does not always increases mobility, like for example when the melt is too viscous as in quartz-bearing rocks. Hence, the simulations indicate that the mechanism suggested by Erismann [1979]
to explain the volume effect based on melting self-lubrication cannot have general validity if the landslide is rigid. A volume effect, on the other hand, resulted when simulated landslides have a mafic (and to some extent intermediate) composition; in agreement with previous experimental and theoretical work [Erismann, 1979]. Indeed, if the landslide is disintegrated, it will have an internal strength of the order of the Coulomb friction. In this case, a volume effect appears more general from our simulations.

[29] Our results also highlighted that lubrication depends critically on delicate properties of the molten layer. The preservation of a thin molten layer for many kilometers in a very energetic and dissipative environment such as the sole of a large rock avalanche is a necessary prerequisite of the model. In a real landslide, the distribution of frictionite is more likely to occur in contiguous limited areas rather than affecting a long sheet of material. Thus, we expect that the volume effect found in this work may be exaggerated. We found that Coulomb friction remains important during the duration of the landslide if the asperity size \( \lambda \) (of the order of the grain size) is larger than a few millimeters; in this case the volume effect is somehow decreased. Additionally, a very viscous (felsic) rock composition results in a molten layer with poor lubricating properties, and this may also mitigate the volume effect for these rocks. The model predicts a much more widespread effect for mafic rather than felsic compositions. Usually, the data from which the volume effect is established (equation (1)) do not discern the different rock compositions. It would be interesting to create such plots with regard to the chemical composition of the rock.

[30] More theoretical studies and field activity should be devoted to assess the role of molten rocks in large landslides. Experiments with granular media in shear cells conducted at high shear rates and pressures could provide important information. A more complete model should also address the role of the granular bed during melting. If grains in the bed are sufficiently large to avoid complete melting but small enough to impede efficient melt percolation, then new physical effects may become important requiring a novel set of model equations: the thermomechanics of incomplete melting commencing at the grain surfaces, the percolation of the melt in the granular medium, and the presence of a solid fraction in the melt affecting the melt effective viscosity. The decrease in the shear resistance possibly leading to long runout will occur via generation of pore melt pressure. Such a model is deferred to a further publication.

[31] To conclude, very high shear rates underneath giant rock avalanches result in a series of poorly understood phenomena like ultracomminution and phase change. We suggest that the problem of rock avalanche dynamics and perhaps also of the long runout of sturzstroms can benefit from a closer glance into the problem of the phase transitions of rocks at severe stress and shear rates, where novel trends may emerge.

Appendix A: Conditions of Stability for a Slab Suspended by Bouncing Grains

[32] In this appendix we show that the scenario in which the upper part of a rock avalanche slides rigidly sustained by a lower layer of bouncing grains is untenable. For simplicity, we consider a plain model of a rigid slab suspended by the collisions of particles underneath (see Figure A1). The slab has mass \( M \) and is kept aloft by \( N \) bouncing grains each of mass \( m \). The slab remains parallel to the terrain inclined with an angle \( \beta \) with respect to the horizontal. During one particle collision against the slab, the component of the slab velocity perpendicular to the terrain \( V \) changes as

\[
V \rightarrow V + \frac{m}{M} \left( \frac{1 + \varepsilon}{2} u_{\perp} - V \right),
\]

where \( \varepsilon \) is the coefficient of restitution of the velocity and \( u_{\perp} \) is the modulus of the velocity component of the particle perpendicular to the terrain.

[33] Considering the impact of all the \( N \) grains and adding the effect of gravity, this component of the slab velocity changes in time as

\[
\frac{dV}{dt} \approx -g \cos \beta + \frac{1}{2} f N m \frac{1 + \varepsilon}{1 + m/M} (u_{\perp} - V),
\]

where \( f = u_{\perp}/D \) is the frequency of collision (for this approximation we assume that all grains have the same perpendicular velocity \( u_{\perp} \)) and \( D \) is the distance between the lower face of the slab and the terrain. We have also assumed that the mean free path of grains is less than the thickness of the shear layer, so that grains do not appreciably collide against each other. The rate of change of the specific kinetic energy per particle in the ensemble of bouncing clasts is \( \frac{dE}{dt} = (1/2) \frac{d(u^2)}{dt} = u \frac{du}{dt} \), where \( u^2 \approx u_0^2 + u_1^2 \), and \( u_1 \) is the velocity of the particle parallel to the slope. This rate must be equal to the energy acquired by particles due to the fall in the gravity field, subtracted of the energy dissipated by collisions with the slab and the basement

\[
\frac{dE}{dt} = u \frac{du}{dt} \approx g u_0 \sin \beta - f m N (1 - \varepsilon^2) u_1^2,
\]
where again we have neglected grain-grain collisions. We also assume energy equipartition for nonrotating grains in two dimensions, i.e., $u_1^2 = u_2^2$. The two conditions for the slab to remain suspended by the grains are that (1) the slab should not accelerate toward the basement, namely, $dV/dt > 0$ and (2) the energy lost per unit time by one grain should be lower than the energy acquired because of the fall in the gravity field, or $dE/dt > 0$. Using the equations above, the two conditions can be recast in the form

$$u_1 = \sqrt{2 \cos \beta \eta \over 2D_g} (1 - \varepsilon) - \sin \beta \over 1 - \varepsilon = u_2,$$

where $\eta = mN/M$ is the ratio between the mass contained in the bouncing particles and the slab mass. The equations show that the particle speed $u$ must be sufficiently large to ensure an adequate transfer of momentum to the slab, but at the same time a too high grain velocity determines high energy dissipation.

A necessary condition to avoid slab collapse is thus that the extremes $u_1 < u_2$, from which we obtain

$$\tan \beta 
\geq \frac{2(1 - \varepsilon)}{\eta}.$$

which (except for the factor 2) appears as an intuitive result. Even for an unrealistically large value for $\eta$ (for example, $\eta \approx 1$ corresponding to the total mass of the bouncing grains comparable to the mass of the slab) and with $\varepsilon \approx 0.5$ we find that the terrain should slope at least 45 degrees for the slab to remain suspended. The above equations are clearly greatly approximated, but the implications introduced (no rotations, absence of grain-grain collisions) go in the direction of increasing mobility even more. It can be concluded that (except possibly during the early sliding phase at steep slope) a giant rock avalanche does not travel suspended by a layer of colliding clasts; it is the early sliding phase at steep slope a giant rock avalanche makes all the difference. It can be concluded that (except possibly during

**Acknowledgments.** Dieter Issler kindly offered many suggestions that improved the form and the content of the manuscript, and generously provided us with the photograph of Figure 5 prior to publication. Useful comments from J. Spray on a previous version are greatly appreciated. The article also benefited from thorough and insightful reviews by M. McSaveney and another anonymous reviewer. This is the International Centre for Geohazards (ICG) contribution 98.

**References**


---

F. V. De Blasio and A. Elverhøi, Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, N-0316 Oslo, Norway.