Recycling fracture surface energy – implications for geodynamics

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1. Introduction

Davies et al. (2019a, b) use laboratory and field data to show that the energy required to extend a crack in brittle fracture ("fracture surface energy", FSE) does not all transform to surface free energy (SFE) as cracking proceeds as suggested in Griffith (1921); much of it remains as elastic body-wave energy, to do further work. At least <90% of energy used in creating new surface area in brittle fracture returns to the system rather than being absorbed as SFE. This energy misconception has remained unquestioned for over a century because progress in quantifying sub-micron debris sizes has only recently made it possible to recognize fragment sizes extending <<1 micron. Now, the true magnitude of new surface created in some fragmentation episodes is dramatically increased. In Davies et al. (2019b) a study of a rock-avalanche deposit finds that 90% of the surface area is borne by sub-micron fragments. The change in perception of fracture energetics does not affect the validity of Griffith fracture mechanics (the energy required to extend a crack in brittle fracture). It deals only with the post-failure fate of this energy. The misconception becomes significant only when the large numbers of very fine fragments created by rapid, high-stress brittle fracture are identified in particle-size distributions. Herein we outline the significance of our revision of fracture energetics to understanding of some geodynamic phenomena with which we are acquainted.

2. Available free energy

The major consequence for fracture energetics is that it recognizes >90% of the elastic strain energy released by breakage of a clast as being transformed to body-wave energy, rather than being absorbed as SFE. This is an order of magnitude more energy radiating through the adjacent material, enhancing grain-flow mobility (Hu et al., 2022) and creating more new surface area than suggested by the Griffith (1921) interpretation.

3. Particle size distributions

3.1. A "Grinding limit"

A size below which rock clasts can no longer form smaller fragments by crushing is suggested (e.g. Kendall, 1978), and estimates of this limit are commonly ~ 1 micron. This is said to correspond with the maximum elastic strain energy that can be stored in a clast of given volume, elastic modulus and specific surface energy being entirely converted into fracture surface energy. The resulting surface area is claimed to determine the minimum size and maximum number of fragments. If, however, most of the elastic strain energy used in fracture is re-used to cause further fracture then more surface area is created, and the minimum fragment size is reduced. The presence of fragments down to tens of nanometers in size in fault gouge and rock-avalanche debris is now commonly reported (Chester et al., 2005; Wilson et al., 2005; McSaveney & Davies, 2007).

3.2. Particle size distribution and agglomerates

Particle-size distributions of fault gouges and rock-avalanche debris are often fractal with a fractal dimension of about 2.6 (Fig. 1(Left); McSaveney & Davies, 2007). These distributions usually show a roll-over departure from a straight line below about 0.6 µm (Fig. 1(a)), which is attributed to failure to accurately measure finer grains. However, the finest debris from a fragmentation event will agglomerate forming larger particles (Reznichenko et al., 2012). Without disaggregation, particle-size analysis treats agglomerates as single particles. Davies et al. (2019b) find grains an order of magnitude smaller after ultrasonic vibration to disaggregate agglomerates (Fig. 1(Right)). Reznichenko et al. (2012) identify agglomerates of ultra-fine fragments in rock avalanche debris (Fig. 3). This is the first specific description of agglomerates, which however are imaged previously in fault gouge (e.g. Yund et al., 1990) without attracting attention.

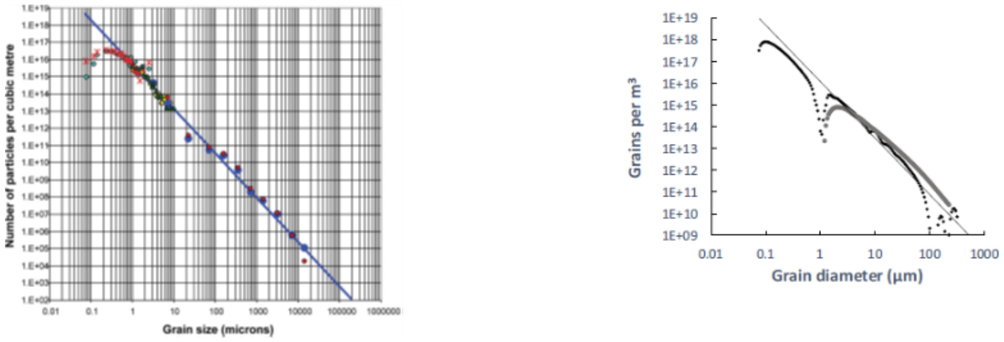

Fig. 1 (Left) Particle-size distributions of debris from Mt Cook and Mt Fletcher rock avalanches, NZ (McSaveney & Davies, 2007). (Right) Particle-size distribution of Acheron rock avalanche, NZ, before (gray points) and after (black points) ultrasonic disaggregation (Davies et al., 2019b).

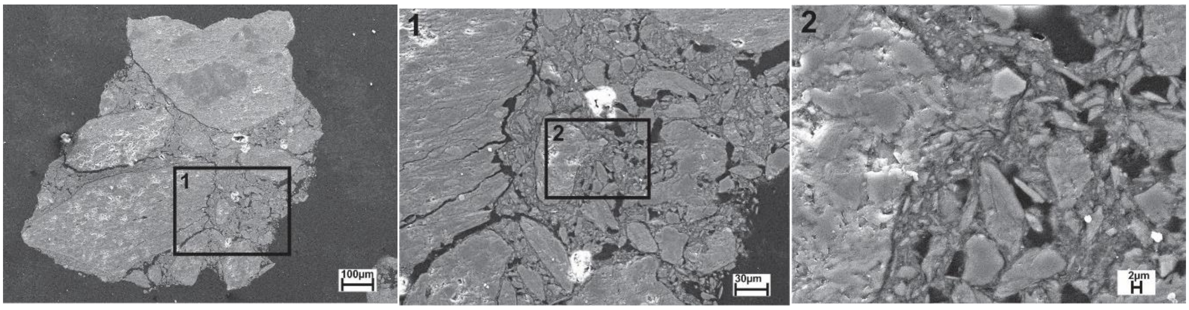

Fig 2 Agglomerates in rock-avalanche debris

Agglomerates in brittle fracture debris are important, because for example:

1. Undetected agglomerates bias particle-size distributions, because the finest grains are masquerading as coarser grains (Fig. 3(b)). This reduces estimates of new surface area created during a fracture event and distorts fragmentation energy budgets (Wilson et al., 2005; Davies et al., 2019b).
2. Agglomerates reflect the creation of ultra-fine grains, and thus of rapid and high-stress processes such as rock avalanching. Their presence in glacial moraines may thus indicate that the moraine formed largely by accumulating supraglacial rock-avalanche debris. This has implications for glacial paleoclimatology (Reznichenko et al., 2012, 2015).

4. Runout of rock avalanches and blockslides

Davies et al. (1999) propose that fragmentation-derived dispersive pressure could explain the high mobility of rock avalanches and apply it to explaining rock-avalanche deposit geometry (e.g. Davies & McSaveney 2002), volcanic debris avalanches (Davies et al., 2010) and block slides (Davies et al., 2006). This explanation is criticized because it appears to contradict the interpretation of fragmentation energetics due to Griffith (1921); e.g. Hungr (2006) states "… fragmentation is an energy-consuming process. Thus while it may promote lateral and longitudinal spreading, it cannot increase the mobility of the center of mass". This criticism is also founded on particle-size distributions that do not include sub-micron sizes, e.g. De Blasio & Crosta (2014) state that "…fragmentation appears to be a minor energy sink for rock avalanches. Davies et al. (2019b) shows an energy balance and sedimentology of the 0.6 Mm^3 Coleridge rock avalanche, and concludes that the potential energy reduction in the emplacement of the deposit is insufficient to explain the energy dissipated during runout and the new rock surface generated, if all FSE transformed to SFE as Griffith (1921) assumes. This, together with the experiments of Davies et al. (2019a), refutes earlier criticisms of this rock-avalanche mobility concept. But see Hu et al. (2022) for an alternative mobility interpretation.

5. Fault rupture, friction and gouge

Davies et al. (2012) suggests that during shear in a fault zone a high dispersive stress generated by gouge-creating fragmentation causes low dynamic friction that leads to large fault displacement. Wilson et al. (2005) studies the size distributions of gouge in the San Andreas fault and in deep South Africa mines, and finds that, under the Griffith (1921) assumption, "…gouge formation consumes ~ 50% of the earthquake energy…" in the latter case. This result has been heavily criticised, but if the Griffith assumption does not apply, it avoids the problem of potential under-prediction of radiated seismic energy due to overestimation of energy loss.

6. Moraine paleoclimatology

Emplacement of a rock avalanche deposit on the ablation surface of a glacier significantly reduces the melting of surface ice (Reznichenko et al., 2010), which can result in glacier advance and subsequent retreat with emplacement of rock-avalanche debris as a terminal moraine. Terminal moraines are often used as paleoclimate proxies, based on the assumption that glacier advances and retreats that form a terminal moraine are caused by climate variations altering glacier mass balance. This is not necessarily the case, however, if the moraine contains agglomerates. An example is New Zealand's Waiho Loop moraine, which is shown to be the result of supraglacial emplacement of a large ($\sim 10^8$ m^3) rock avalanche (Tovar et al., 2008; Alexander et al., 2014) about 11,000 years ago; prior to this explanation the Waiho Loop was considered as evidence that the influence of the Younger Dryas extended to the Southern Hemisphere (Denton & Hendy, 1994).

7. Volcanic ash generation

The 2010-2011 eruptions of Iceland's Eyjafjallajökull and Grimsvötn showed some of the impacts of volcanic ash on society. Dürig et al. (2012) show that fine ash is a product of brittle fracture during explosive volcanism; its formation may represent a substantial part of the mechanical energy released in an explosive eruption. Dürig et al. (2012) estimate 86–94% loss of total input energy as fracture energy under the Griffith (1921) assumption. However, this assumed energy loss appears likely to underestimate the new particle surface area able to be generated in an eruption, and hence the quantity of fine ash that can form destructive pyroclastic density currents or threaten air travel.

8. Geohazard assessment

Over-estimation of energy loss associated with rock fragmentation will generally underestimate the energy available for material motion during the progress of the phenomenon causing fragmentation. For example, the Griffith (1921) assumption leads to underestimation of available energy in blockslides and rock avalanches, potentially leading to underestimation of hazard-zone extent. In earthquakes, overestimating the proportion of tectonic strain energy lost to SFE implies overestimating the source seismic energy though unnecessary compensation. Underestimating the number of ash particles from an eruption can lead to underestimating the magnitude of ash clouds and hence the occurrence of pyroclastic flows and duration of impacts on air travel. Identification of agglomerates in moraines implies that rock-avalanche material is present; this means in turn that future rock avalanches may be part of the hazard spectrum in that location. If the agglomerates are not identified, the hazard status of the location may be misunderstood.

9. Discrete element simulations

In discrete element modelling of rock fragmentation (e.g. Lisjack & Grasselli, 2014) rock masses are represented by notional particles held together by shear and tensile bonds; fracture occurs when these bonds break. The Griffith (1921) assumption implies that tensile forces in bonds reduce to zero when breakage occurs ("…the bond is deleted…"; André et al., 2013) and the bond energy becomes zero and lost from the system. Since this is not the case, such simulations are unrealistic.

10. Summary

As investigations of rock fracture increasingly recognise sub-micron fragments, it is increasingly important to acknowledge that energy involved in molecular bond breakage is not absorbed as surface free energy, but is recycled and contributes to further fracture and system dynamics. This does not affect the dynamics of the fracture phenomena but substantially affects the grading and nature of rock fracture debris.

11. Reference list

André, D., Jebahi, M., Iordanoff, I., Charles, J.L. & Néauport, J., 2013. Using the discrete element method to simulate brittle fracture in the indentation of a silica glass with a blunt indenter. Computer Methods in Applied Mechanics and Engineering, 265, pp.136-147.

Chester, J.S., Chester, F.M. & Kronenberg, A.K., 2005. Fracture surface energy of the Punchbowl fault, San Andreas system. Nature, 437(7055), pp.133-136.

Davies, T.R.H., McSaveney, M.J. & Hodgson, K.A., 1999. A fragmentation-spreading model for long-runout rock avalanches. Canadian Geotechnical Journal, 36(6), pp.1096-1110.

Davies, T.R.H. & McSaveney, M.J., 2002. Dynamic simulation of the motion of fragmenting rock avalanches. Canadian Geotechnical Journal, 39(4), pp.789-798.

Davies, T.R.H., McSaveney, M.J. & Beetham, R.D., 2006. Rapid block glides: slide-surface fragmentation in New Zealand's Waikaremoana landslide. Quarterly Journal of Engineering Geology and Hydrogeology, 39(2), pp.115-129.

Davies, T.R.H., McSaveney, M.J. & Reznichenko, N.V., 2019a. What happens to fracture energy in brittle fracture? Revisiting the Griffith assumption. Solid Earth, 10(4), pp.1385-1395.

Davies, T.R.H., Reznichenko, N.V. & McSaveney, M.J., 2019b. Energy budget for a rock avalanche: fate of fracture-surface energy. Landslides, pp.1-11: DOI 10.1007/s10346-019-01224-5.

De Blasio, F.V. & Crosta, G.B., 2014. Simple physical model for the fragmentation of rock avalanches. Acta Mechanica, 225(1), pp.243-252.

Denton, G.H. & Hendy, C.T., 1994. Younger Dryas age advance of Franz Josef glacier in the Southern Alps of New Zealand. Science, 264(5164), pp.1434-1437.

Griffith, A. A., 1921. The Phenomena of Rupture and Flow in Solids, Phil. Trans. Royal Soc. A, 221, 163–198.

Hu W.; Xu, Q.; McSaveney M.; Huang R.; Wang Y.; Chang C.S.; Gou H. & Zheng Y., 2022. The intrinsic mobility of very dense grain flows. Earth and Planetary Science Letters, 580, 15 February 2022, 117389.

Hungr, O., 2006. Rock avalanche occurrence, process and modelling. In Landslides from massive rock slope failure (pp. 243-266). Springer, Dordrecht.

Kendall, K., 1978. The impossibility of comminuting small particles by compression. Nature, 272(5655), pp.710-711.

Lisjak, A. & Grasselli, G., 2014. A review of discrete modeling techniques for fracturing processes in discontinuous rock masses. Journal of Rock Mechanics and Geotechnical Engineering, 6(4), pp.301-314.

McSaveney, M. & Davies, T., 2007. Rockslides and their motion. In Progress in landslide science (pp. 113-133). Springer, Berlin, Heidelberg.

Reznichenko, N., Davies, T., Shulmeister, J. & McSaveney, M., 2010. Effects of debris on ice-surface melting rates: an experimental study. Journal of Glaciology, 56(197), pp.384-394.

Reznichenko, N.V., Davies, T.R., Shulmeister, J. & Larsen, S.H., 2012. A new technique for identifying rock avalanche–sourced sediment in moraines and some paleoclimatic implications. Geology, 40(4), pp.319-322.

Reznichenko, N.V., Davies, T.R. & Winkler, S., 2016. Revised palaeoclimatic significance of Mueller Glacier moraines, Southern Alps, New Zealand. Earth Surface Processes and Landforms, 41(2), pp.196-207.

Yund, R.A., Blanpied, M.L., Tullis, T.E. & Weeks, J.D., 1990. Amorphous material in high strain experimental fault gouges. Journal of Geophysical Research: Solid Earth, 95(B10), pp.15589-15602.

Wilson, B., Dewers, T., Reches, Z. & Brune, J. 2005. Particle size and energetics of gouge from earthquake rupture zones. Nature 434, 749-752.