Rock Avalanche Sedimentology—Recent Progress

Anja Dufresne

Abstract

Since Yarnold and Lombard (Field trip guidebook—Pacific section, 9–31, 1989) presented a systematic facies model for ancient rock avalanche deposits in dry climates, more landslide researchers have organized observations from one or more case studies into general sedimentological descriptions and facies models (references are provided in the main text). These recent advances show that rock avalanches are multi-facies deposits. Retention of source stratigraphy and a general three-part division of a coarse-grained, largely unfragmented upper part or carapace, a finer-grained body of diverse sedimentology, and a basal facies influenced by interactions with runout path materials are the most common observations. The greatest variation in the grain size distribution and comminution intensity occurs between the bouldery carapace and the matrix-supported interior, i.e. the body facies which constitutes the largest deposit volume. Most striking, but not surprising, is the highly heterogeneous nature of the body facies with a number of sub-facies and discontinuity layers, which must reflect highly heterogeneous states of stress within the deforming granular mass. These features within the body facies are the most important for studying those emplacement dynamics that are not affected by boundary conditions, such as runout path sediments. Where the base is exposed, a characteristic basal facies with substrate injections and/or a basal mixed zone and/or deformation features can be found, usually above a very sharp contact to the underlying, disrupted sediments. The overall commonalities of internal rock avalanche features indicate that some basic processes must act universally during their emplacement. The value of these sedimentological models and descriptions lies in contrasting universally valid features with those that are a function of unique geological, topographic, or structural settings, or which might suggest different/additional emplacement dynamics of a specific deposit.

Keywords

Rock avalanche • Sedimentology • Depositional facies

Introduction

Pioneering rock avalanche research (from Heim 1932 onwards) focused primarily on morphometric analyses; including some, but relatively general descriptions of deposit sedimentology. More detailed sedimentological investigations emerged later in the century with the work of Yarnold and Lombard (1989), and today encompasses further systematic studies: Friedmann (1997), Strom (1994), Wassmer et al. (2004), Pollet and Schneider (2004), Dunning (2004), Crosta et al. (2007), Hewitt (2009), Gruber et al. (2009), Dunning and Armitage (2011), Pedrazzini et al. (2013), Weidinger et al. (2014), Dufresne and Dunning (submitted), and Dufresne et al. (in press). These systematic studies,

A. Dufresne (✉)
RWTH Aachen University, Engineering Geology
and Hydrogeology, Lochnerstr. 4-20, 52064 Aachen, Germany
e-mail: anja@adufresne.com

M. Mikoš et al. (eds.), *Advancing Culture of Living with Landslides*,
DOI 10.1007/978-3-319-53498-5_14

together with singular observations found throughout the literature, improve our understanding of rock avalanche emplacement processes and provide ground truth data for any theoretical, kinematic or numerical emplacement model. A number of commonalities of internal rock avalanche features indicate that some basic processes act universally during their emplacement, whereas local peculiarities in the sedimentology of some deposits could point to influencing factors, such as topography, substrates, rock mechanical properties (lithology), source predisposition (joint spacing, bedding, etc.), or emplacement dynamics specific to this event. The following is a brief synopsis of the state-of-the-art of research on rock avalanche sedimentology.

Depositional Facies

Source stratigraphy is preserved in all large rockslide, rock avalanche, and volcanic debris avalanche deposits despite long (up to 10 s km) runout distances (Heim 1932; Johnson 1978; Yarnold and Lombard 1989; Strom 1994; Vallance et al. 1995; Capra et al. 2002; Abdrakhmatov and Strom 2006; Geertsema et al. 2006; Hewitt et al. 2008; Dufresne et al. 2009, 2015; Weidinger et al. 2014; Roverato et al. 2015). Neither significant topographic interference, such as runup or overtopping e.g. 200 m high ridges, nor changes in thickness disrupt the stratigraphic sequence within the granular mass. Stretching and thinning of units may, however, occur (Strom 2006). Furthermore, a three-part division of a coarse upper carapace, a body facies of diverse sedimentology and a basal facies in contact to and often mixed with the underlying substrates is common to these large mass movements (Friedmann 1997; Wassmer et al. 2004; Pollet and Schneider 2004; Dunning 2004; Crosta et al. 2007; Hewitt 2009; Gruber et al. 2009; Dunning and Armitage 2011; Weidinger et al. 2014; Dufresne et al. in press).

Carapace

The carapace (Davies and McSaveney 2004) is an open network of large angular boulders covering most rock avalanche deposits (Heim 1932; Abele 1974; Prager 2010; Davies and McSaveney 2012). It is the coarsest of all facies (Fig. 1a). On very thin (~2 m; Shugar and Clague 2011) supra-glacial rock avalanches, a bouldery carapace is often absent (Jibson et al. 2006), but this is not necessarily so for all supra-glacial rock avalanches. Likewise, the properties (mechanical strength, joint spacing, etc.) of some lithologic units preclude carapace formation (e.g. the fine-grained carbonate-siliciclastic rauhwacken of the Tschirgant RA, which do not form clasts larger than a few dm in the deposit; Dufresne et al. 2016). Carapace boulder alignments and orientations can indicate local spreading directions (Gates 1987; Blair 1999; Shugar and Clague 2011) and debris extension (Dufresne et al. 2016). A decrease in boulder size has been observed for the Frank Slide (Canada; Charrière et al. 2015), which indicates that in some cases, stresses are transferred to the open surface layer, respectively that progressive breakage may occur even in the upper, non-fragmenting debris.

The transition from the carapace to the underlying body is often marked by a blocky facies (Fig. 1b; Dufresne et al. in press) with a block-in-matrix fabric (Medley 1994).

Body Facies and Sub-facies

The body facies constitutes most of the deposit thickness and contains highly heterogeneous facies and fabric distributions. Zones of concentrated shear (Fig. 1c, i, j) are found adjacent to clasts that experienced minimal (jigsaw-fractured clasts; Fig. 1g) or no breakage (survivor clasts). Both facies are, in turn, surrounded by highly fragmented debris (Fig. 1e) in which grains of all sizes are in contact with each other (Dufresne and Dunning, submitted). In the past, inverse grading has been alluded to, but recent progress has shown it to be limited to the upper deposit section; if at all present (Dunning 2006; Genevois et al. 2006; Crosta et al. 2007; Dunning and Armitage 2011; Weidinger et al. 2014).

Survivor clasts are clasts of significantly larger size than their surrounding matrix (Dufresne et al. 2009; Imre et al. 2010) and reflect size-dependent comminution processes—in a granular flow in which all grains are of the same

Fig. 1 **a** Coarse carapace of the LeMarocche rock avalanche deposit in Italy (note people for scale in *white circle*). Images (**b**) through (**i**) illustrate the diverse sedimentology of the body facies. **b** A blocky facies is typical for the transition of the carapace to the body, but may also occur within the body facies in some deposits (e.g. the Brusson rock avalanche, Italy). **c** Multiple shear bands in the Round Top rock avalanche, New Zealand. **d** Jigsaw-fractured facies, where boundaries between larger, original clasts become blurred, but the individual fragments are not disaggregated (LeMarocche, Italy). **e** The "typical" interior of rock avalanche deposits consists of the fragmented facies (Tschirgant rockslide-rock avalanche, Austria). **f** Preserved stratigraphic banding in the mylonitic Round Top rock avalanche (New Zealand) demonstrates different degrees of clast comminution in the different lithologic bands. **g** Individual jigsaw-fractured clast (Köfels, Austria). **h** Fabric dominated by the structures of the source rock shows crude alignment (indicated by *white dashed line*) of the clasts along their original beddings/foliations (Brusson rock avalanche, Italy; see also Schoeman 2016). **i** Frictionite (*white borders*) within a shear band (*pink borders*) at the Köfels rockslide, Austria. **j** Example of a basal mixed zone and associated structures (distal Tschirgant rock avalanche, Austria) ▶


(a)
(b)
20 cm
(c)
(d)
(e)
(f)
(g)
5 cm
(h)
20 cm
(i)
5 cm
(j)
rock avalanche
substrate injection
shear bands
basal mix zone
substrate

material, it requires a grain of equal or larger size to crush another (McSaveney and Davies 2006). Discontinuity sets in jigsaw-clasts maintain the same orientation despite long travel distances (Brideau and Procter 2015; Pedrazzini et al. 2013). Shear is concentrated along discrete bands of less than a few decimeters in thickness and some meters in length (Yarnold and Lombard 1989; Crosta et al. 2007; Davies et al. 2010). Melting of rock, forming frictionites (e.g. Erismann 1979; Hermanns et al. 2006; Weidinger and Korup 2009), is associated with granular shear bands (Fig. 1e). Shear bands are not exclusive to the base, but are distributed throughout the debris thickness and travel path length (Roverato et al. 2015; Dufresne and Dunning, submitted). Thus, while the granular mass is deforming and fragmenting, survivor and jigsaw clasts, as well as shattered megablocks document the deformation history and local flow directions otherwise disguised within the debris of grains many orders of magnitude different in size.

These diverse features of the body facies reflect the highly heterogeneous states and distribution of stresses throughout the entire deforming granular mass (McSaveney and Davies 2006).

Basal Facies

Along the lowest few meters, a distinct basal facies (Fig. 1j) where sediments from the runout path are entrained, mixed and mingled into the avalanche debris (basal mixed zone; Hungr and Evans 2004; Hewitt 2009; Hewitt et al. 2008; Dufresne 2012) is often present, primarily in the distal deposit areas. With or without a basal mixed zone, the contact of rock avalanche deposits to underlying sediments is usually knife-sharp; some even feature beheaded boulders with their top carried a short distance along the basal contact. Where shear forces are less strong, fine basal material may flow around such obstacles (Robinson et al. 2015). Folds, faults, rip-up clasts, and flame injections are common. Basal mixed zone material may also form diapiric intrusions into the overlying body facies. A recent study found that intrusions of substrate sediments into the basal or body facies are often surrounded by a "halo" of fine shear bands (Fig. 1j), which must form ideal pathways for injection of loaded sediments into an otherwise coarse granular mass (Dufresne et al., in press).

Boundary Conditions/Influencing Factors

Source structures (bedding thickness, joint spacing, tectonic fault zones, etc.), rock (mass) mechanical properties, topographic interference, and interaction with runout path sediments can add a degree of complexity in the development of depositional facies in rock avalanches. For example, bedding-controlled failures produce an additional 'structured facies' and shear localization along original layer contacts (Pollet and Schneider 2004; Wassmer et al. 2004; Pedrazzini et al. 2013). Shear localization (Fig. 2) is, however, also seen in deposits without major bedding-controlled failures. Collision with topography may constrain fragmentation in

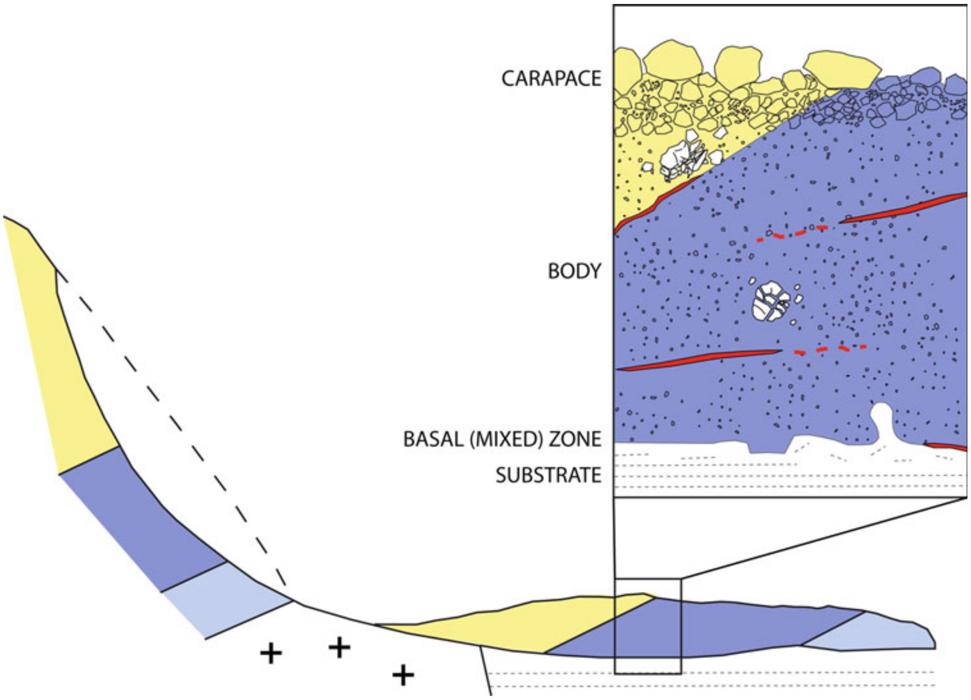

Fig. 2 Simplified illustration showing *1* retained source stratigraphy in the deposit, *2* the main depositional facies carapace, body, and base, *3* sub-facies such as blocky zones (beneath carapace), shear bands (*red lines*), jigsaw-fractured clasts/facies (*white clasts* in the body), and the fragmented facies (*stippled fill*), and *4* deformation features at the basal contact

the deposit interior (Hewitt 2001), where the jigsaw-facies is more prominent than fragmented debris (Dufresne et al., in press), whereas surface clast sizes are comparatively smaller in these deposit parts (Adushkin 2006).

Grain Size Distributions

Grain sizes in rock avalanches range from 100-m-blocks down to sub-µm particles. Whereas the bulk weight is constituted by the large blocks, the highest number of particles lies in the fine fractions, with powders (i.e. silts, clays and finer particles) constituting over 99% of the total number of grains. It is the characteristics (e.g. angular shapes) and high proportion of this fine fraction that has been successfully used by Reznichenko et al. (2012) to identify rock avalanche-derived debris in moraines. Different sampling strategies have been employed to study the grain size variations in rock avalanche deposits. Bulk sampling concentrated on and identified trends of overall grain size reduction with depth and distance (e.g. Crosta et al. 2007). A facies-based approach, on the other hand, aims at understanding the underlying processes that lead to the formation of each facies, such as breakage along rock-type specific planes of weakness in the coarse-particle-dominated jigsaw-fractured facies, fragmentation creating new surfaces and irregularly shaped grains in the fragmented facies (approaching bell-shaped histograms), and bimodal, fines-dominated zones of shear concentration (Dufresne and Dunning, submitted). Facies “maturation” with distance is a tentative interpretation of histograms from samples of the same lithology along the runout path (Dufresne et al. in press).

Concluding Remarks

Good progress has been made in recent years in understanding rock avalanche sedimentology. Rock avalanches and rockslides are multi-facies deposits that cannot be defined by one overall grain size distribution. Rather, the heterogeneous make-up of the deposit interior reflects highly heterogeneous stress distributions in time and space during runout. Field and analytical evidence rules out any exotic hypothesis (such as air layer lubrication) to explain their runout distances and emplacement processes—heterogeneous fragmentation suffices to explain the diverse fabric of these compelling deposits (Dufresne and Dunning, submitted).

Acknowledgements This research was funded by the German Research Foundation grant DU1294/2-1; project “Long-runout landslides: the influence of lithology on comminution, (micro-) structures, morphology, and runout”.

References

Abdrakhmatov K, Strom AL (2006) Dissected rockslide and rock avalanche deposits; Tien Shan, Kyrgyzstan. In: Evans SG, Scarascia-Mugnozza G, Strom AL, Hermanns RL (eds) Landslides from massive rock slope failure. Nato Sci Ser IV, Earth Environ Sci 49:551–570

Abele G (1974) Bergstürze in den Alpen, ihre Verbreitung, Morphologie und Folgeerscheinungen. Wissen-schaftliche Vereinshefte 25:230p

Adushkin VV (2006) Mobility of rock avalanches triggered by underground nuclear explosions. In: Evans SG, Scarascia-Mugnozza G, Strom AL, Hermanns RL (eds) Landslides from massive rock slope failure. Nato Sci Ser IV, Earth Environ Sci 49:267–284

Blair TC (1999) Form, facies, and depositional history of the North Long John rock avalanche, Owens Valley, California. Can J Earth Sci 26:855–870

Brideau MA, Procter JN (2015) Discontinuity orientation in jigsaw clasts from volcanic debris avalanche deposits and implications for emplacement mechanism. GeoQuébec, 20–23 Sept 2015, Abstract 614

Capra L, Macías JL, Scott KM, Abrams M, Garduño-Monroy VH (2002) Debris avalanches and debris flows transformed from collapses in the Trans-Mexican Volcanic Belt, Mexico—behavior, and implications for hazard assessment. J Volcanol Geoth Res 113 (1–2):81–110

Charrière M, Humair F, Froese C, Jaboyedoff M, Pedrazzini A, Longchamp C (2015) From the source area to the deposit: collapse, fragmentation and propagation of the Frank Slide. GSA Bull 128 (1–2):332–351

Crosta GB, Frattini P, Fusi N (2007) Fragmentation in the Val Pola rock avalanche, Italian Alps. J Geophys Res 112:23p

Davies TR, McSaveney MJ (2004) Dynamic fragmentation in landslides: application to natural dam stability. In: Evans SG, Strom AL (eds) Abstract volume, NATO advanced research workshop: security of natural and artificial rockslide dams. Kyrgyzstan, Bishkek, pp 7–13

Davies TR, McSaveney MJ, Kelfoun K (2010) Runout of the Socompa volcanic debris avalanche, Chile: a mechanical explanation for low basal shear resistance. Bull Volc 72(8):933–944

Davies TR, McSaveney MJ (2012) Mobility of long-runout rock avalanches. In: Clague JJ, Stead D (eds) Landslides—types, mechanisms, and modeling. Cambridge University Press, UK, pp 50–59

Dufresne A (2012) Granular flow experiments on the interaction with stationary runout path material and comparison to rock avalanche events. Earth Surf Proc Land 37:1527–1541

Dufresne A, Davies TR, McSaveney MJ (2009) Influence of runout-path material on emplacement of the Round Top rock avalanche, New Zealand. Earth Surf Proc Land 35:190–201

Dufresne A, Bösmeier A, Prager C (in press) Rock avalanche sedimentology—case study and review. Earth-Sci Rev

Dufresne A, Dunning S (submitted) Process-dependence of grain size distributions in rock avalanche deposits

Dufresne A, Prager C, Bösmeier A (2016) Insights into rock avalanche emplacement processes from detailed morpho-lithological studies at the Tschirgant deposit (Tyrol, Austria). Earth Surf Proc Land 41 (5):587–602

Dunning S (2004) Rock avalanches in high mountains. PhD thesis, University of Luton, UK

Dunning S (2006) The grain size distribution of rock avalanche deposits in valley-confined settings. Italian J Eng Geol Environ, Spec Issue 1:117–121

Dunning SA, Armitage PJ (2011) The grain-size distribution of rock-avalanche deposits: implications for natural dam stability. In: Evans SG, Hermanns RL, Strom A, Scarascia-Mugnozza G (eds) Natural and artificial rockslide dams. Lect Notes Earth Sci 33:479–498

Erismann TH (1979) Mechanisms of large landslides. Rock Mech 12 (1):15–46

Friedmann SJ (1997) Rock-avalanche elements of the Shadow Valley Basin, Eastern Mojave Desert, California: processes and problems. J Sediment Res, Sect A: Petrol Process 67(5):792–804

Gates WCB (1987) The fabric of rock avalanche deposits. Bull Assoc Eng Geol 24(3):389–402

Geertsema M, Hungr O, Schwab JW, Evans SG (2006) A large rockslide-debris avalanche in cohesive soils at Pink Mountain, Northeastern British Columbia, Canada. Eng Geol 83:64–75

Genevois R, Armento C, Tecca PR (2006) Failure mechanisms and runout behavious of three rock avalanches in the North-eastern Italian Alps. In: Evans SG, Scarascia-Mugnozza G, Strom AL, Hermanns RL (eds) Landslides from massive rock slope failure. Nato Sci Ser IV, Earth Environ Sci 49:407–427

Gruber A, Strauhal T, Prager C, Reitner JM, Brandner R, Zangerl C (2009) Die "Butterbichl-Gleitmasse"—eine fossile Massenbewegung am Südrand der Nördlichen Kalkalpen (Tirol, Österreich). Swiss Bulletin für angewandte Geologie 12(1–2):103–134

Heim A (1932) Bergsturz und Menschenleben. Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich 77:218p

Hermanns RL, Blikra LH, Naumann M, Nilsen B, Panthi KK, Stromeyer D, Longva O (2006) Examples of multiple rock-slope collapses from Köfels (Ötz valley, Austria) and western Norway. Eng Geol 83:94–108

Hewitt K (2001) Catastrophic rockslides and the geomorphology of the Hunza and Gilgit river valleys, Karakoram Himalaya. Erdkunde 55:72–93

Hewitt K (2009) Catastrophic rock slope failures and late Quaternary developments in the Nanga Parbat-Haramosh Massif, Upper Indus basin, northern Pakistan. Quatern Sci Rev 28(11–12):1055–1069

Hewitt K, Clague JJ, Orwin JF (2008) Legacies of catastrophic rock slope failures in mountain landscapes. Earth-Sci Rev 87:1–38

Hungr O, Evans SG (2004) Entrainment of debris in rock avalanches: an analysis of a long runout-out mechanism. Geol Soc Am Bull 116 (9–10):1240–1252

Imre B, Laue J, Springman SM (2010) Fractal fragmentation of rocks within sturzstroms: insight derived from physical experiments within the ETH geotechnical drum centrifuge. Granular Matter 12:267–285

Jibson RW, Harp EL, Schulz W, Keefer DK (2006) Large rock avalanches triggered by the M 7.9 Denali Fault, Alaska, earthquake of 3 November 2002. Eng Geol 83:144–160

Johnson B (1978) Blackhawk landslide, California, US. In: Voight B (ed) Rockslides and avalanches: natural phenomena, vol 1. Elsevier, Amsterdam, pp 481–504

McSaveney MJ, Davies TR (2006) Rockslides and their motion. In: Sassa K, Fukuoka H, Wang F, Wang G (eds) Progress in landslide science. Springer, Heidelberg, pp 113–133

Medley EW (1994) The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks). PhD thesis, University of California, Berkeley

Pedrazzini A, Jaboyedoff M, Loye A, Derron MH (2013) From deep-seated slope deformation to rock avalanche: destabilization and transportation models of the Sierre landslide (Switzerland). Tectonophysics 605:149–168

Pollet N, Schneider J-LM (2004) Dynamic disintegration processes accompanying transport of the Holocene Flims sturzstrom (Swiss Alps). Earth Planet Sci Lett 221(1–4):433–448

Prager C (2010) Geologie, Alter und Struktur des Fernpass Bergsturzes und tiefgründiger Massenbewegungen in seiner Umgebung (Tirol, Österreich). PhD thesis, Univeristät Innsbruck, Austria

Reznichenko NV, Davies TR, Shulmeister J, Larsen SH (2012) A new technique for identifying rock avalanche-sourced sediment in moraines and some paleoclimatic implications. Geology 49 (4):319–322

Robinson TR, Davies TR, Reznichenko NV, De Pascale GP (2015) The extremely long-runout rock avalanche in the Trans Altai range, Pamir Mountains, southern Kyrgyzstan. Landslides 12:523–535

Roverato M, Cronin S, Procter J, Capra L (2015) Textural features as indicators of debris avalanche transport and emplacement, Taranaki volcano. GSA Bull 127(1–2):3–18

Schoeman C (2016) The Brusson rock avalanche, northwestern Italian Alps. MSc Thesis, University of Freiburg, Germany, 52 pp

Shugar D, Clague JJ (2011) The sedimentology and geomorphology of rock avalanche deposits on glaciers. Sedimentology 58(7):1762–1783

Strom AL (1994) Mechanism of stratification and abnormal crushing of rockslide deposits. 7th international IAEG congress, pp 1287–1296

Strom AL (2006) Morphology and internal structure of rockslides and rock avalanches: grounds and constraints for their modelling. In: Evans SG, Scarascia-Mugnozza G, Strom AL, Hermanns RL (eds) Landslides from massive rock slope failure. Nato Sci Ser IV, Earth Environ Sci 49:305–328

Vallance JW, Siebert L, Rose WI Jr, Girón JR, Banks NG (1995) Edifice collapse and related hazards in Guatemala. J Volcanol Geoth Res 66(1–4):337–355

Wassmer P, Schneider J-L, Pollet N, Schmitter-Voirin C (2004) Effects of the internal structure of a rock-avalanche dam on the drainage mechanism of its impoundment, Flims Sturzstrom and Ilanz paleo-lake, Swiss Alps. Geomorphology 61:3–17

Weidinger JT, Korup O (2009) Frictionite as evidence for a large Late Quaternary rockslide near Kanchenjunga, Sikkim Himalayas, India—implications for extreme events in mountain relief destruction. Geomorphology 103(1):57–65

Weidinger JT, Korup O, Munack H, Alternberger U, Dunning S, Tippelt G, Lottermoser W (2014) Giant rockslides from the inside. Earth Planet Sci Lett 389:62–73

Yarnold JC, Lombard JP (1989) Facies model for large rock avalanche deposits formed in dry climates. In: Colburn IP, Abbott PL, Minch J (eds) Field trip guidebook—Pacific section. Soc Econ Paleontol Mineral 62:9–31