SUPPLEMENTARY MATERIAL:

Mechanisms of slab avalanche release and impact in the Dyatlov Pass incident in 1959

Johan Gaume, EPFL and Alexander Puzrin, ETH Zurich

Table of contents:

Supplementary Note 1: Forensic evidence of a delay in the slab release

The following reported evidences (Buyanov and Slobtsov 2014) allowed us to evaluate a realistic range for the delay between the moment the Dyatlov group made the cut in the slope to install the tent and the time of the incident:

1. *The time of the cut in the slope*. The sunset in Burmantovo (66 km away from the accident location) on the 1st of February 1959 was at 5:02 pm. The tent was likely build before the sunset, and the construction started with cutting the slope (the last photo showing the cut was taken during a daylight, Fig. 1a). Assuming that it would take at least an hour to build a tent, it is likely that the cut was made not later than at 4:00 pm
2. *The lost lanterns*. The fact that lanterns have been found outside the tent by the search team indicates that the incident occurred during night-time.
3. *The time when their watches stopped*. According to reports of rescue operations, watches generally stop in such cold weather (-25°C, winds up to 10 m/sec) approximately 1 hour after the death. Slobodin's watch stopped at 8:45am, Thibault's watch stopped at 8:14am and 8:39am and Dyatlov's watch stopped at 5:31am. This leads to a time of death approximately between 4:30 and 7:30am.
4. *The last meal.* The post-mortem investigation revealed that they died 6 to 8 hours after their last meal.
5. *The survival time.* Rescue operations report that under temperatures as low as -25°C and without appropriate shelter and clothing (Igor Dyatlov's body was found on an open slope, not wearing shoes and a jacket), the maximum survival time would be around 2 to 3 hours.

   Conclusion. Given the previous information, we can back calculate the time at which a potential avalanche could release between 1:30 and 5:30am as well as a range for the delay between the time of the cut in the slope and the avalanche between 9.5 and 13.5 hours.

Supplementary Note 2: Other forensic evidences and reported facts

Conclusions of the autopsy and reported injuries

We summarize here the results from the post-mortem evaluation of the Soviet investigation for the nine members of the Dyatlov group (based on the English translation of the official Soviet autopsy reports). Note that the bodies of Yuri Doroshenko, Yuri Krivonischenko, Igor Dyatlov and Zinaida Kolmogorova were found in the Cedar at a 1.5km distance from the tent, 26 days after the incident and their autopsy was made on March 4. Rustem Slobodin was found on March 5 approximately 480m from the Cedar and his autopsy was performed on March 8. Bodies of Lyudmila Dubinina, Semyon Zolotaryov, Aleksander Kolevatov and Nicolas Thibeaux-Brignolle were found in a Ravine (also called "Den") on May 5 by a local tribesman. Their autopsy was performed on May 9.

1. *Yuri Doroshenko*'s post-mortem examination showed:
    a. damage such as multiple abrasions, skin wounds and bruises
    b. he had third and fourth degree frostbites on most fingers and toes
    c. he had meninges oedema, strong hyperaemia in internal organs, cardiac cavities full of dark blood petechiae in the gastric mucosa and an excessive full bladder

The conclusion of the autopsy performed by Soviet experts was that he died from hypothermia based on evidences 1b and 1c. The reported external injuries were considered as "non-life threatening" and could be explained by a fall on rocks or ice or other objects. The data of the examination shows that his last meal was taken 6 to 8 hours before death.

2. *Yuri Krivonischenko*'s post-mortem examination showed:
    a. lesions, bruises and skin wounds
    b. the tip of his nose was missing
    c. fingers, toes and ears had frostbites and burns of the second to third degree
    d. meninges swelling, blood-filled internal organs, overfilling of the pericardium with dark liquid blood, existence of Vishnevsky spots on the stomach, overfilling of the bladder

The conclusion of the autopsy performed by Soviet experts was that he died from hypothermia based on evidences 1c and 1d. The reported external injuries were considered as "non-life threatening" and could be explained by a fall on rocks or ice or other objects. The missing nose tip was found without traces of blood which suggests that he was bitten by an animal after his death. The reported burns were inflicted by close contact to a fire. The data of the examination shows that his last meal was taken 6 to 8 hours before death.

3. *Igor Dyatlov*'s post-mortem examination showed:
    a. damage in the form of graze wounds, scratches and skin wounds
    b. third to fourth degree frostbites of the extremities
    c. meninges oedema, strong hyperaemia of internal organs, filling of heart cavities with dark blood, Vischnevsky spots on the gastric mucosa, overfilled bladder.

The conclusion of the autopsy performed by Soviet experts was that he died from hypothermia/freezing based on evidences 1b and 1c. The reported external injuries were considered as light and not damaging to health and could be explained by a fall on stones or ice or other objects. The data of the examination shows that his last meal was taken 6 to 8 hours before death.

4. *Zinaida Kolmogorova*'s post-mortem examination showed:
    a. abrasions and skin wounds
    b. fourth-degree frostbite on the third terminal phalanges of the fingers
    c. swelling of meninges, dramatic plethora of internal organs, dark liquid blood in the heart, Vishnevsky spots on the gastric mucosa

The conclusion of the autopsy performed by Soviet experts was that she died from hypothermia/freezing based on evidences 1b and 1c. The reported external injuries could be explained by a fall on stones or ice or other objects. The data of the examination shows that her last meal was taken 6 to 8 hours before death.

5. *Rustem Slobodin*'s post-mortem examination showed:
    a. abrasions, scrapes and graze wounds
    b. a fracture of the left frontal lobe bone
    c. third to fourth degree freezing of the fingers
    d. swelling of meninges, blood-filles organs, Vishnevksy spots on the stomach mucosa

The conclusion of the autopsy performed by Soviet experts was that he died from hypothermia/freezing based on evidences 1c and 1d and based on the absence of explicit bleeding under the meninges. The reported external injuries could be explained by a fall or impact on stones or ice or other objects. The data of the examination shows that his last meal was taken 6 to 8 hours before death.

6. *Lyudmila Dubinina*'s post-mortem examination showed:
    a. damage to the soft tissue of the head
    b. eyeballs and tongue are missing
    c. multiple bilateral rib fractures
    d. hemorrhage into the right ventricle and internal bleeding into the thoracic cavity

The conclusion of the autopsy performed by Soviet experts was that she died because of an impact of great force causing severe trauma to the chest based on evidences 6c and 6d. The trauma was caused while she was alive and is the result of a high force impact.

7. *Aleksander Kolevatov*'s post-mortem examination showed:
    a. defects in soft tissues and whitened skin
    b. opened wound behind the ear

The conclusion of the autopsy performed by Soviet experts was that he died from low temperatures. The conclusions for this case are not based on very strong evidence. The soft tissue is thought to be a result of post-death changes in the body which was located in the water for some time before it was found.

8. *Semyon Zolotaryov*'s post-mortem examination showed:
    a. multiple fractures of the right ribs
    b. internal hemorrhaging to the pleural cavity
    c. opened wound behind the ear

The conclusion of the autopsy performed by Soviet experts was that he died due to a high-power impact to the chest.

9. *Nikolay Thibeaux-Brignolle*'s post-mortem examination showed:
    a. corporal damage of the soft tissue and whitened skin at the extremities
    b. fracture of the base and the vault of the cranium
    c. prolific amount of bleeding under the meninges

The conclusion of the autopsy performed by Soviet experts was that he died due to great force leading to a pressure fracture. The soft tissue is thought to be a result of post-death changes in the body which was located in the water for some time before it was found.

Summary

Buyanov and Slobtsov (2014) attribute Dubinina's and Zolotarev's broken ribs, as well as Thibeaux-Brignolle's and Slobodin's skull injuries to the fact that they were sleeping in the end of the tent which was hit by the slab (Figure SF1). Dubinina was likely sleeping on her back, hence the bilateral rib fractures, while Zolotarev on his side (unilateral fractures). Thibeaux's fracture at the base of the cranium is attributed to the fact that he regularly used his photo camera as a pillow, resulting in high concentrated force as his head was hit by the slab.

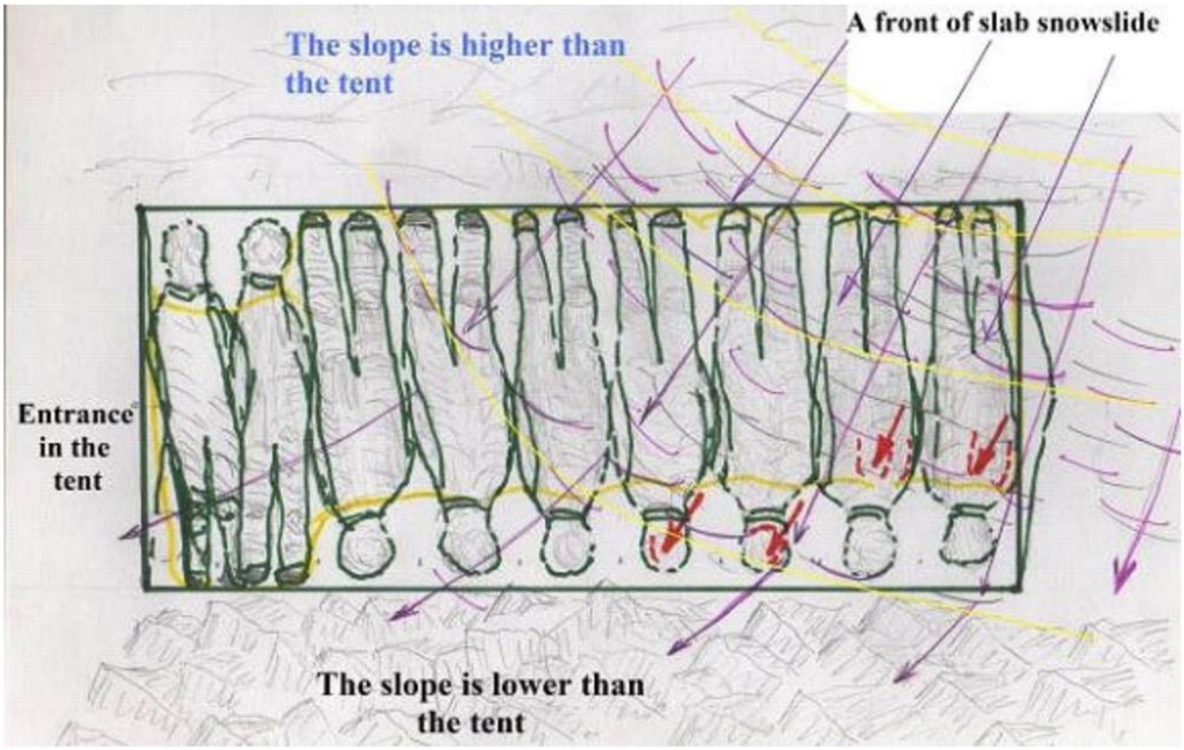

Figure SF1: Positions of Dyatlov's group in the tent and potential dynamics of the avalanches (Buyanov and Slobtsov, 2014). Courtesy of Evgeniy Buyanov.

The Soviet investigation performed at that time reported that the chest and skull injuries were not characteristics of typical avalanche accidents. This is hardly surprising, because most of the avalanche victims are not being hit against a rigid obstacle and mainly die from asphyxia. However, in a 21-year review of patterns of death among avalanche fatalities in Canada, Boyd et al. (2009) showed that in the cases where the avalanche death was caused by a single-system trauma, chest trauma was the most common injury (46%) while the head injury was the second most common one (42%).

Observations at the tent location

Signs of avalanche

While the search team did not report obvious avalanche signs, several evidences tend to justify the avalanche assumption including:

- The snow cut performed by the Dyatlov group of more than 1m high seen in the last Picture (Fig. 1a) disappeared in agreement with the MPM simulation in which the cut part of the slope has been filled by the broken snow slab.
- No snow was found inside the tent which implies that the tent was covered with snow otherwise it would have been torn apart by the wind, filled with snow and the belongings of the Dyatlov group would have been scattered on the slope.
- Other signs such as a broken ski pole and a crack in the roof of the tent.

Run-out-angle

The run-out angle (McClung et al. 2006) from the top of the slope to the tent location is around 16° which makes it physically impossible that an avalanche released at the top of the slope would reach the tent (Eichar 2013). This means that only a small snow slab could release above the tent due to the cut and external loading (assumed here to be related to wind transport snow).

Terrain features

It has been reported (Buyanov and Slobtsov 2014) that the slope above the tent was highly irregular with "steps" formed by ledges of low hillocks (Fig. SF2). Snowfall and wind are known to smooth terrain variability (Filhol and Sturm 2019) which explains why the average slope angle was found smaller than the local terrain angle right above the tent, estimated around 28°.

With time (snowfall and wind events), the snowpack gets thicker in hollows below the hillock and thinner on the ledges. This explains the choice of the Dyatlov group to dig at this particular location in order to have a better protection from the wind. In addition, given the cut height visible in Dyatlov's last picture, the top of the tent would still have been strongly affected by the wind which suggests that they could have built a parapet by putting the cut snow blocks close to the edge of the cut as an additional safety measure (Fig. SF3). Finally, given that a ski pole has been place on the slope above the tent, the slab has been damaged which can lead to a reduction in the tensile resistance of the slab and thus more instability.

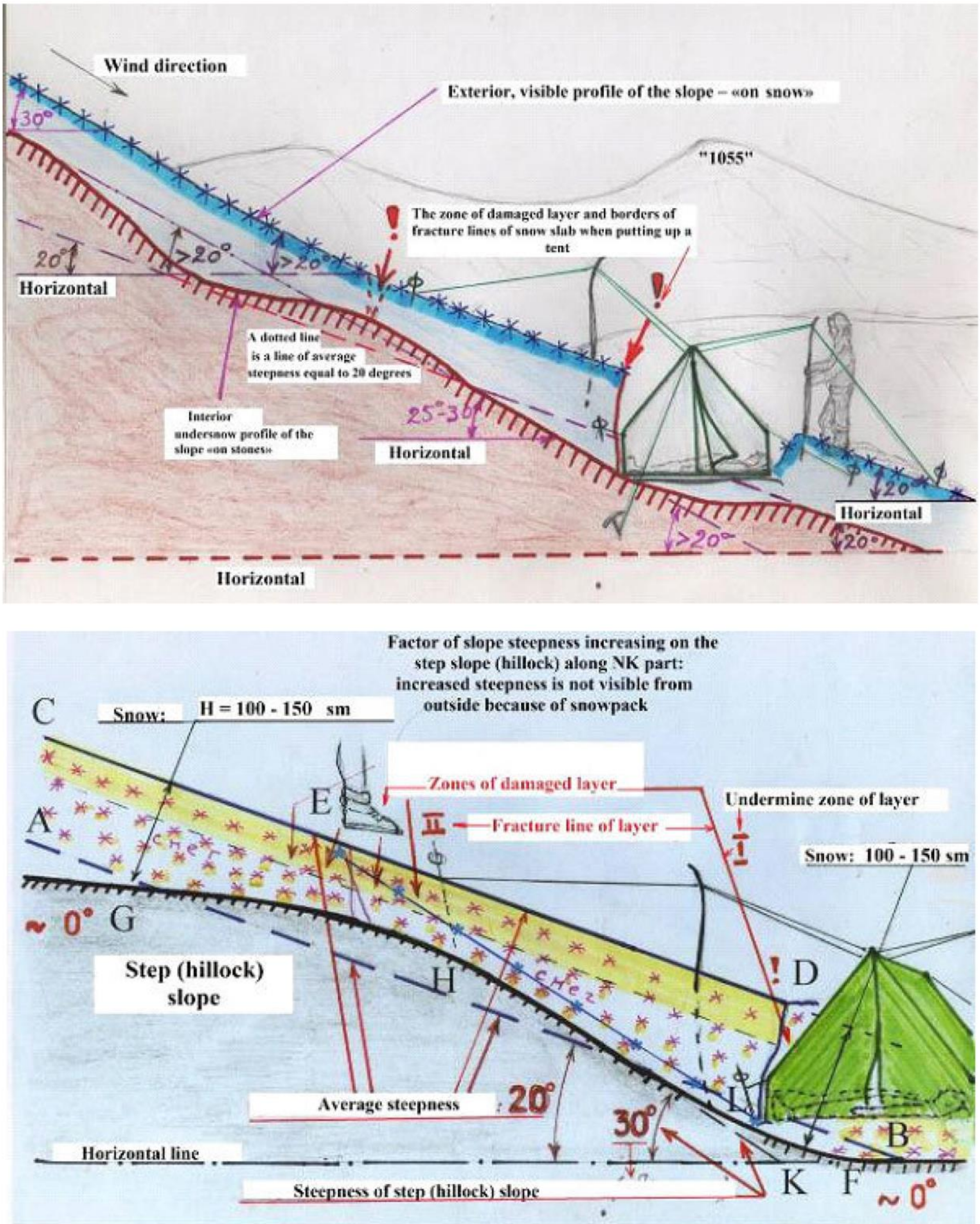

Figure SM2. (top) Snow cover (blue) and terrain (red) profiles near the tent. (bottom) zoom of the terrain profile above the tent. From Buyanov and Slobtsov (2014). Courtesy of Evgeniy Buyanov.

Figure SF3. Schematic of the Dyatlov group's tent installed for heavy weather and high winds i.e. deepened down the slope with a parapet for wind protection. (Buyanov and Slobtsov, 2014). Courtesy of Evgeniy Buyanov.

Similar events

We report here similar events mentioned by Buyanov and Slobtsov (2014) in which an undercut in the slope to install a tent led to a catastrophic snow slab avalanche. In addition, we present the results of several field tests performed by snow and avalanche scientists which show that the conditions for a snow slab to be released and to slide can be met, even on mild slopes (Buyanov 2020) which are naturally stable.

Oleg Romanov's group

In 1982, a group led by Oleg Romanov mysteriously disappeared on the 6th of February in 1982. The bodies were found on July 08 after a long search. Reported evidences from this case show that they made a cut in the slope to install the tent and that strong winds occurred that night. The snow slab above the tent fell and covered the tent while they were sleeping (their watches all stopped at the same time due to a strong impact). In addition, the unsuccessful searches made shortly after the group disappeared at the location where the bodies were found report a "total absence of traces of an avalanche".

M. Gorilovsky's group

In 1983, the group led by M. Gorilovsky made an undercut within a snow slope to install the tent in a canyon at 6.30pm near a flat Northen slope. Five persons from the group started to dig while two other persons went on a gentle slope to check the place. These two people initiated a failure in a buried weak layer which propagated a led to the release of a snow slab which killed the 5 people digging.

Baranov – Verpatov's group

In 1993, some Ukrainian mountaineers climbed the Hantengri peak in the central Tian Shan. This group made an undercut in the slope to prepare a flat region for the tent close to the mountain ridge. Another group made a snow cave 500m below. In the next morning, the latter group found the Ukrainian people digging out the bodies of their friends. Here, a small snow slab was also triggered by the undercut in the slope.

Eremkin's group

In 1988 in the south of Polar Ural, an avalanche on a camp site resulted in 13 victims. The similarities with the Dyatlov pass incident are striking: a 25-30° slope, an undercut to install the tent, increased slope above right above the tent. A small wind slab of thickness between 0.4 and 1m released while the people were inside the tents. Some people survived by digging themselves out including Eremkin, Master of Sports who considered that the Dyatlov group was victim of similar snow slab avalanche.

Other similar cases

Several additional similar cases have been reported by Buyanov and Slobtsov (2014). Yet, similarities with the Dyatlov incident were not obvious and have thus not been described here.

The Rutschblock avalanche field stability test

The Rutschblock (RB) test was developed by the Swiss army in the 1960 (Föhn 1987) and is used to interpret snowpack stability (Jamieson and Johnston 1993). The RB consists in isolating a snow volume of ~2x2 m over the thickness of the snowpack. The result of the test – the RB score – is defined on a scale from 1 to 7 where 1 means that the snow blocks fails during digging or cutting while 7 means no failure, even after stepping on the block (RB=2), bending the knees (RB=3), jumping (RB=4), jumping again (RB=5) and jumping without skis (RB=6). In general, RB scores lower than 3 are associated with low snowpack stability while RB scores higher than

5 are associated with a good snowpack stability (Monti et al. 2016). Here, we report in Fig. SF4 the results of 831 RB tests performed by researchers from the University of Calgary. Figure SF4A and SF4B shows that the snowpack can fail regardless of the slope angle. One can notice that the snowpack can fail without significant external force (RB=1,2,3) even for low slope angle values, even though the general trend is that stability increasing with decreasing slope angle (Figure SF4C). Finally, we note that for the conditions of the Dyatlov pass incident, more than 40% of the RB tests performed led to the sliding of the block (Figure SF4C).

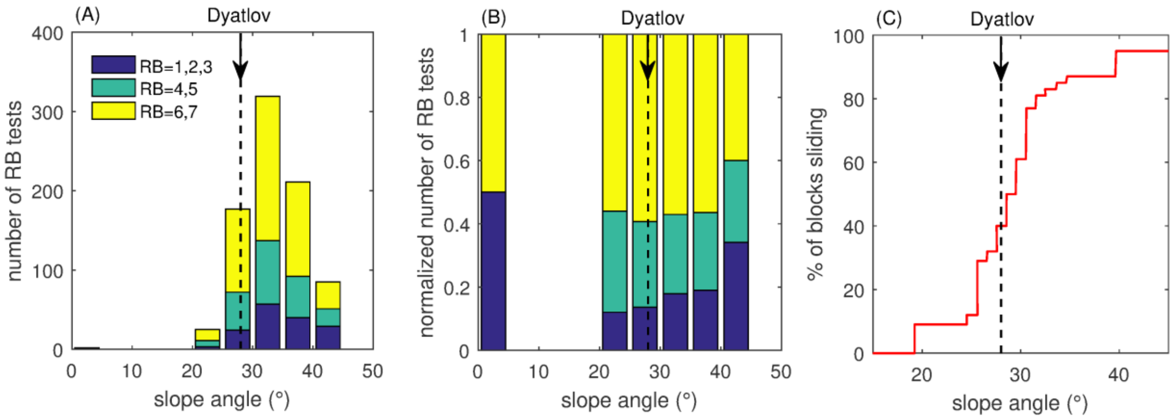

Figure SF4. Slope angle distribution (A) and normalized distribution (B) corresponding to 831 Rutschblock Tests. (C) Percentage of block sliding as a function of slope angle for 831 Rutschblock

Supplementary Note 3: Meteorological data

Buyanov and Slobtsov (2014) made a detailed review of meteorological conditions at before, during and after the Dyatlov incident. We report in Fig. SF5 temperature data from the closest meteorological station in Bormotovo (66km from the incident place). Two major information can be extracted from these temperature charts: 1) the average temperature the night of the incident was -20° and the minimum temperature around -30°; The average temperature in January before the incident was around -15° and temperature variations were very large (more than -15° variations in temperature during 1 or 2 days of observations). The first fact tells us that the survival time without appropriate clothes is of a few hours only. The second point indicates that the snowpack was submitted to very large temperature gradient which are known to lead to the formation of depth hoar snow crystals (Fukuzawa and Akitaya 1993). This confirms observations of the presence of depth hoar at the tent location and nearby locations (Buyanov and Slobtsov 2014). This snow type has a very low cohesion and is particularly dangerous when buried below a cohesive and dense snow slab as reported in the Dyatlov case.

Concerning the wind, wind speeds between 2 and 4 m/s were measured at the Ivdel station (117 km from the Dyatlov pass) while wind speeds up to 9 km/h were measured in (Bormotovo Buyanov and Slobtsov 2014). Expert-based estimations of maximum wind speeds between 10-15 m/s were made at the location of the Dyatlov tent. Based on these measurements and estimations, we chose a range of realistic average wind speed between 4 and 10 m/s.

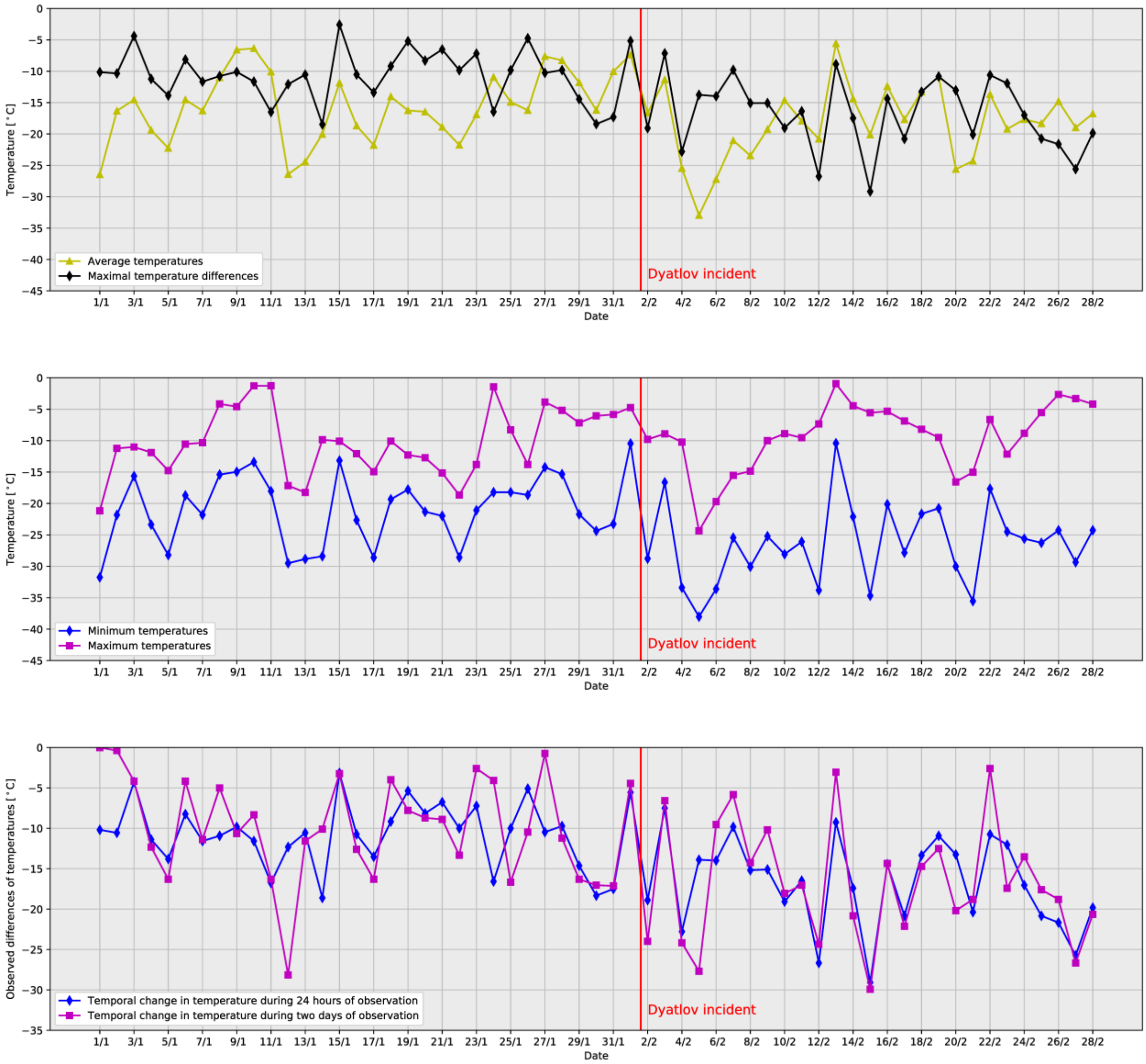

Figure SF5. (top) Average temperature and maximal temperature difference, (middle) minimum and maximum temperatures; (bottom) temperature changes during 24 and 48 hours of observations.

Supplementary Note 4: Numerical validation of the analytical model

We performed purely elastic MPM numerical simulations to validate the evolution of the shear stress in the weak layer in the vicinity of the cut as a function of increasing slab thickness. The same parameters as in the analytical model have been chosen (see SF6) and we considered a fully sintered slab. While some small discrepancies can be noticed, the general agreement between the numerical and analytical model is reasonable (Fig. SF6).

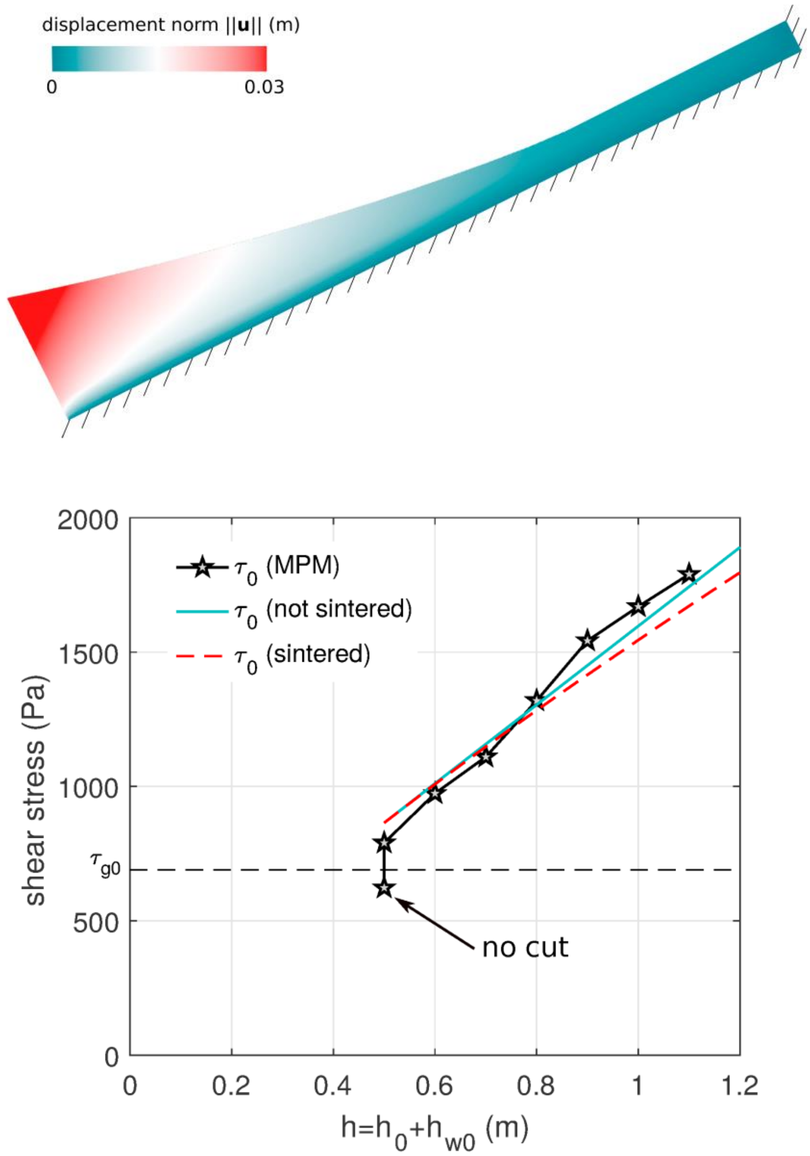

Figure SF6. Top: total displacement of MPM particles in the case of h=1 m. Bottom: shear stress as a function of slab height for the MPM simulation and the two bounds of the analytical model.

Supplementary Note 5: MPM avalanche and impact simulations

Avalanche MPM simulation

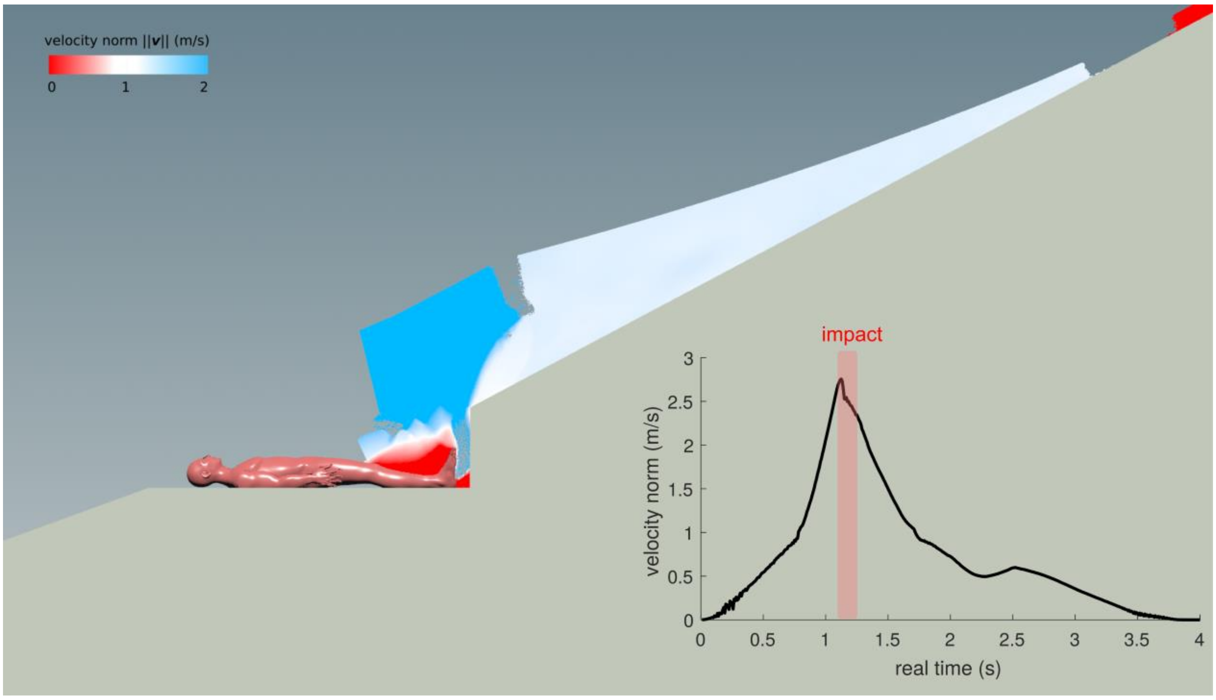

Figure SF7. Spatial distribution of the velocity norm before the impact of the wind snow slab. This figure also illustrates the typical sizes of snow blocks before the impact. Inset: maximum value of the velocity norm of the wind snow slab as a function of time during the MPM avalanche simulation.

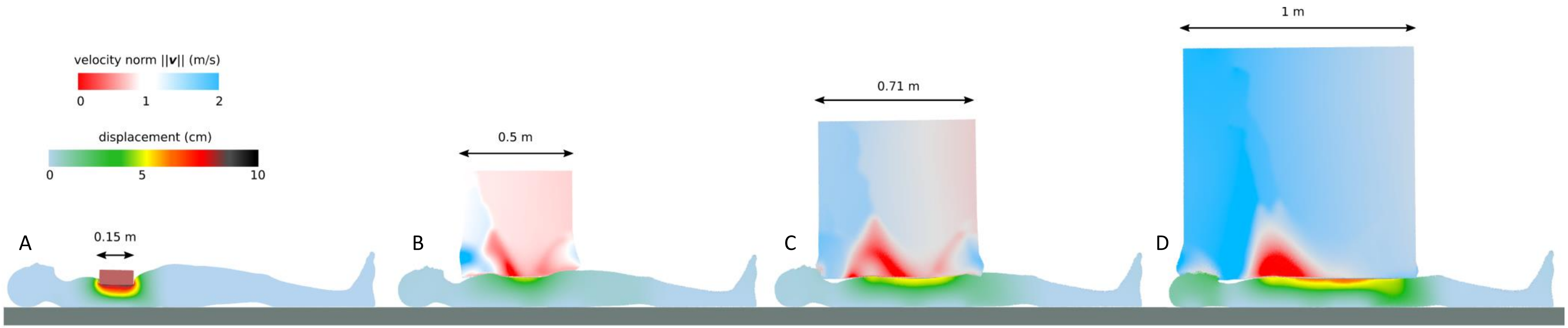

Figure SF8. Three dimensional simulations of thorax impact: A: impact of a rigid rectangular box (0.15 m x 0.15 m x 0.06 m) of 10 kg and initial velocity 7 m/s in lines with the crash test laboratory experiments of Kroell et al. (1974) with restrained back. B, C and D: impact of an elastoplastic snow box of density 400 kg/m^3 and different volumes (V_A=0.125 m^3, V_B=0.25 m^3, V_C=0.5 m^3) with initial velocity 2 m/s. The out-of-plane dimension of the snow block is 0.5 m.

Supplementary Note 6: Model parameters

1. Parameters of the analytical model

Geometry

Geometric parameters for the plane strain model in Fig 4a have been extracted from the investigations of the Dyatlov case (Buyanov and Slobtsov 2014). According to the field data, the planar weak layer was parallel to the steep slope of the local step (hillock), whose inclination was estimated in the range of $25° - 30°$. Based on this data, the average value of $\alpha = 28°$ was adopted for the inclination of the weak layer. The same source allowed for estimating the varying depth of the weak layer, starting as $h_0 = 0.5\ m$ at the cut ($x = 0$) and decreasing uphill until it reaches at $x \geq l_c = 4\ m$ the portion of the slope with the constant depth of the weak layer $h_c = 0.1\ m$. The length of the cut $b = 6.5\ m$ was calculated as the length of the tent ($4.5\ m$) plus 1.0 m on each side of the tent to allow for its installation.

Snow properties

Elastic length of the snow slab was adopted as $l_{e0} = 1.0\ m$, corresponding for $h_0 = 0.5\ m$ to the Young's modulus of the slab $E = 8\ MPa$ (van Herwijnen et al. 2016), shear modulus of the weak layer $G = 1\ MPa$ (Gaume et al. 2017) and the thickness of the depth hoar weak layer $d = 20\ cm$. Densities of the snow slab and the wind transported snow have been taken as $\rho = 300\ \frac{kg}{m^3}$ and $\rho_w = 400\ \frac{kg}{m^3}$, respectively (Paterson 1994).

The lower bound of the initial (pre-cut) lateral snow pressure coefficient K_0 can be estimated assuming that the snow slab is an elastic material with the Poisson ratio ν: $K_0 = \frac{\nu}{1-\nu}$. As a first approximation, $K_0 = 0.43$ was calculated using the Poisson's ratio of $\nu = 0.3$ for the slab (Mellor 1975). The upper bound for K_0 is calculated by using Jaky's plasticity theory based formula for a normally consolidated granular material: $K_0 = 1 - \sin \varphi_s$, where φ_s is the angle of internal friction of the snow in the slab. Adopting the friction in the slab as $\varphi_s = 25°$ (de Montmollin 1978), results in $K_0 = 0.58$. In the paper, we adopt an average value of $K_0 = 0.5$.

Concerning internal friction of the weak layer, Reiweger et al. (2015) report values between 12 and 28° with an average of 20°. For cohesion, Jamieson and Johnston (2001) measured values typically between 0.2 and 1.5 kPa and Reiweger et al. (2015) reported a cohesion value of 0.17 kPa. The representative values of $\varphi = 20°$ and $c = 0.44$ kPa were used in the paper.

Wind transported snow deposition

The deposition flux value $Q = 0.008\ kg\ m^{-1}\ s^{-1}$ calculated based on the analytical model and the estimated range of delay corresponds to a range of possible average wind velocities between approximately 2 and 12 m/s (Fig. SF9, Sturm and Stuefer 2013). These values encompass the reported range of katabatic wind velocities (4-10 m/s) in the night of the Dyatlov Pass accident (Buyanov and Slobtsov 2014).

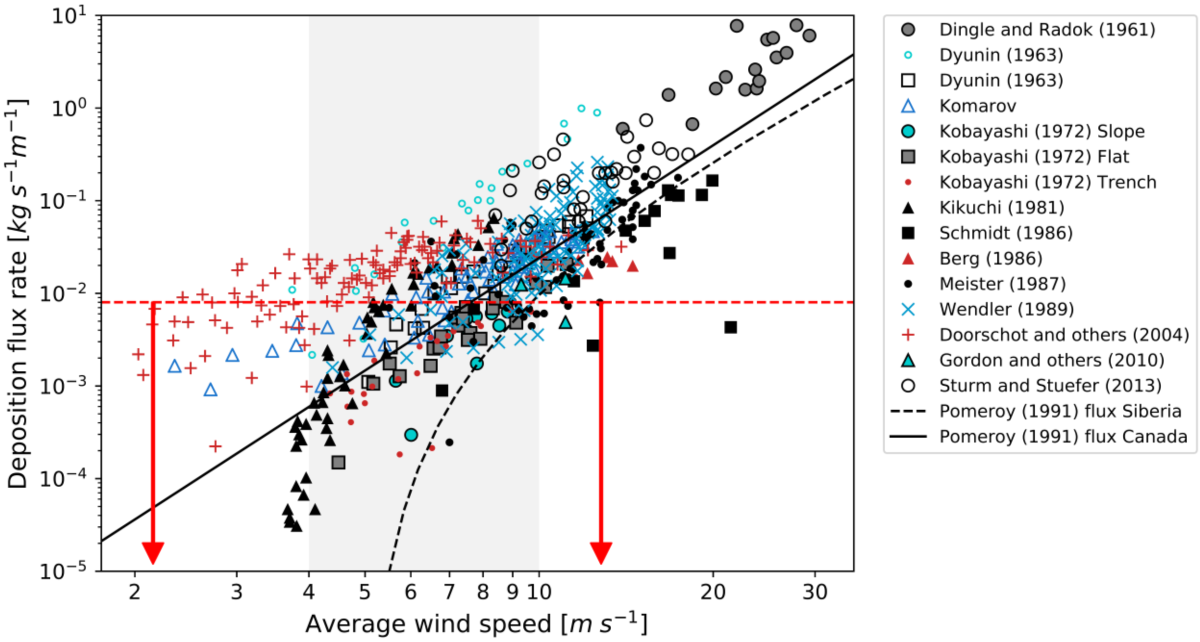

Figure SF9. Deposition flux rate behind a parapet as a function of the average wind speed (based on Sturm and Stuefer 2013). The grey area represents the range of wind speeds reported the night of the 1st of February close to the Dyatlov pass. The red arrows represent the extreme values of wind speed measured for a flux of 0.008 kg/m/s.

2. Parameters of the MPM snow model

The simulated slope bed surface has an inclination of 28° and a dynamic friction angle of 22°. The snow above the slope has a density $\rho = 300\ kg/m^3$ with a varying slab depth. The slab depth at the cut is equal to $h_0/\cos\alpha$ and it is equal to $h_c/\cos\alpha$ for $x = l_c$. The wind-transported snow has a density $\rho = 400\ kg/m^3$ and a depth $h_w/\cos\alpha$ at the cut and smoothly decreases to zero for $x = l_w = 2.5m$ given by the analytic study. The Young's moduli of the snow slab (E=8 MPa) and wind-transported slab (E_w=17 MPa) layers were derived from density based on the experiments of van Herwijnen et al. (2016). The Poisson's ratio was taken equal to 0.3 (Mellor 1975). The tensile strength of the snow slab and wind-transported slab layers were taken equal to 6 and 10 kPa, respectively, based on snow density and according to the experiments of Jamieson and Johnston (1990). For both the snow slab and the wind transported slab, we defined $M = 0.8$ which leads to angle of friction of 21° (Reiweger et al. 2015) and a hardening coefficient $\xi = 5$ leading to a brittle snow slab behavior (Gaume et al. 2018). The value of β was chosen equal to 0.2 for the snow slab and to 0.1 for the wind transported snow slab (Reiweger et al. 2015; Gaume et al. 2018a, 2018b, 2019)

3. Biomedical parameters

Concerning the human body, the elastic modulus is chosen equal to 0.215 MPa to obtain a maximum deformation of the thorax of 49%, similar to that obtained from crash tests performed on human cadavers with restrained back leading to fatal injuries (Kroell et al. 1974). The Poisson's ratio was taken equal to 0.35 based on Chawla et al. (2006). The injury criterion was based on the AIS (Abbreviated Injury Scale, Fenner et al. 1971) and relates the injury rating to the maximum normalized deflection of the thorax (Fig. SF10).

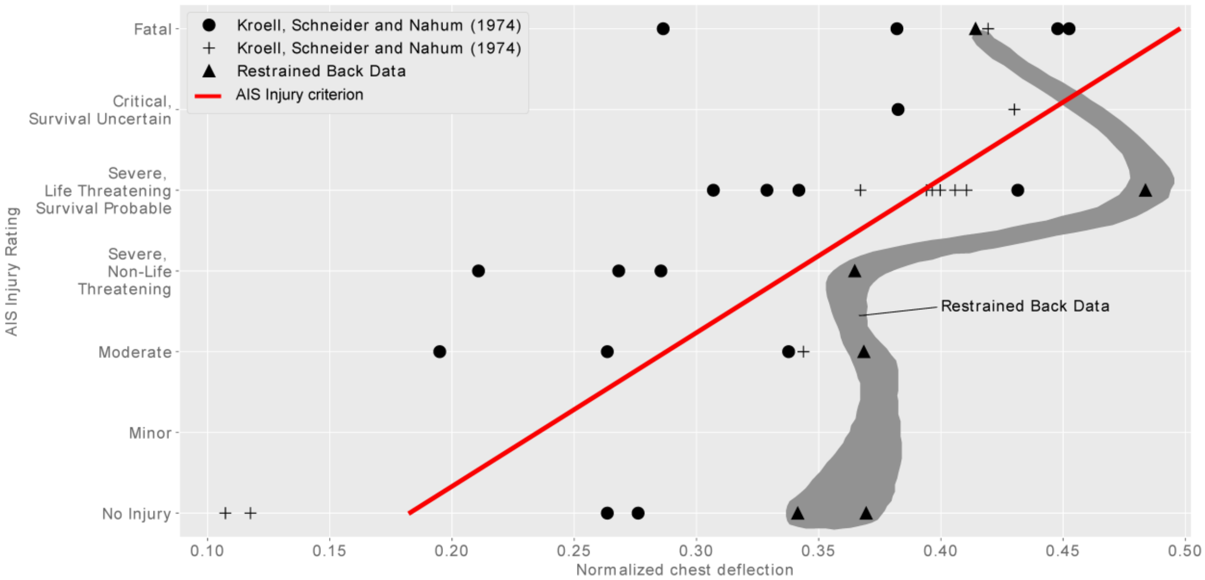

Figure SF10. Injury rating as a function of the maximum normalized deflection during the crash tests. Based on data from Kroell et al. (1974).

Supplementary Note 8: Description of supplementary videos

Supplementary Movie 1: 2D MPM simulation of the Dyatlov slab avalanche illustrating the volumetric plastic strain.

Supplementary Movie 2: 2D MPM simulation of the Dyatlov slab avalanche illustrating the absolute velocity of the snow slab.

Supplementary Movie 3: 3D MPM simulation of the GM crash test (10 kg rigid block with a 7 m/s impact velocity).

Supplementary Movie 4: 3D MPM simulation of a snow block impact (400 kg/m^3 and 0.125 m^3 volume block with 2 m/s impact velocity).

Supplementary Movie 5: 3D MPM simulation of a snow block impact (400 kg/m^3 and 0.25 m^3 volume block with 2 m/s impact velocity).

Supplementary Movie 6: 3D MPM simulation of a snow block impact (400 kg/m^3 and 0.5 m^3 volume block with 2 m/s impact velocity).

Supplementary References

1. Barraclough, T. W., Blackford, J. R., Liebenstein, S., Sandfeld, S., Stratford, T. J., Weinländer, G., & Zaiser, M. (2017). Propagating compaction bands in confined compression of snow. Nature Physics, 13(3), 272-275. doi:10.1038/nphys3966
2. Buyanov E.V. and Slobtsov B.E. (2017) Mystery of the Dyatlov group death. (Taina gibeli gruppy Dyatlova). Litres, ISBN 978-5040256921
3. Buyanov 2020 On the nature of avalanche formation in mild slopes (in Russian), mountain.RU, 9235, http://www.mountain.ru/article/article_display1.php?article_id=9235
4. Chawla, A., Mukherjee, S., & Karthikeyan, B. (2006). Mechanical properties of soft tissues in the human chest, abdomen and upper extremities. Institution of Engineers, J. Mechanical Engineering.
5. Fenner, H. A., Flamboe, E. E., Nelson, W. D., & Hames, L. N. (1971). Field application and research development of the abbreviated injury scale (No. 710873). SAE Technical Paper. doi: 10.4271/710873
6. Filhol, S., & Sturm, M. (2019). The smoothing of landscapes during snowfall with no wind. Journal of Glaciology, 65(250), 173-187. doi: 10.1017/jog.2018.104
7. Fukuzawa, T., & Akitaya, E. (1993). Depth-hoar crystal growth in the surface layer under high temperature gradient. Annals of Glaciology, 18, 39-45. doi: 10.3189/S026030550001123X
8. Gaume, J., van Herwijnen, A., Chambon, G., Wever, N., & Schweizer, J. (2017). Snow fracture in relation to slab avalanche release: critical state for the onset of crack propagation. 11, 217-228. doi: 10.5194/tc-11-217-2017
9. Gaume, J., Gast, T., Teran, J., van Herwijnen, A., & Jiang, C. (2018). Dynamic anticrack propagation in snow. Nature communications, 9(1), 1-10. doi: 10.1038/s41467-018-05181-w
10. Heierli, J., Gumbsch, P., & Zaiser, M. (2008). Anticrack nucleation as triggering mechanism for snow slab avalanches. Science, 321(5886), 240-243. doi: 10.1126/science.1153948
11. Jamieson, J. B., & Johnston, C. D. (1990). In-situ tensile tests of snow-pack layers. Journal of Glaciology, 36(122), 102-106. doi: 10.3189/S002214300000561X
12. Jamieson, B., & Johnston, C. D. (2001). Evaluation of the shear frame test for weak snowpack layers. Annals of Glaciology, 32, 59-69. doi: 10.3189/172756401781819472

13. Kroell, C. K., Schneider, D. C., & Nahum, A. M. (1974). Impact tolerance and response of the human thorax II (No. 741187). SAE Technical Paper. doi: 10.4271/741187
14. McClung, D. M. (1979). Shear fracture precipitated by strain softening as a mechanism of dry slab avalanche release. Journal of Geophysical Research: Solid Earth, 84(B7), 3519-3526. doi: 10.1029/JB084iB07p03519
15. McClung, D. M. (2009). Dimensions of dry snow slab avalanches from field measurements. Journal of Geophysical Research: Earth Surface, 114(F1). doi: 10.1029/2007JF000941
16. McClung, D., & Schaerer, P. A. (2006). The avalanche handbook. The Mountaineers Books.
17. Mellor, M. (1977). Engineering properties of snow. Journal of Glaciology, 19(81), 15-66.
18. Paterson, W. S. B. (1994). Physics of glaciers. Butterworth-Heinemann.
19. de Montmollin, V. (1978). Introduction à la rhéologie de la neige (Doctoral dissertation, Universite Scientifique et Medicale de Grenoble).
20. Reiweger, I., Gaume, J., & Schweizer, J. (2015). A new mixed-mode failure criterion for weak snowpack layers. Geophysical research letters, 42(5), 1427-1432. doi: 10.1002/2014GL062780
21. Sigrist, C. (2006). Measurement of fracture mechanical properties of snow and application to dry snow slab avalanche release (Doctoral dissertation, ETH Zurich).
22. Sturm, M., & Stuefer, S. (2013). Wind-blown flux rates derived from drifts at arctic snow fences. Journal of Glaciology, 59(213), 21-34. doi: 10.3189/2013JoG12J110