A general theory of rock glacier creep based on in-situ and remote sensing observations

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¹ | SUPPORTING INFORMATION
### TABLE 1  Dataset used for the analysis of rock glacier thickness, driving stresses and creep rates. From borehole investigations. From InSar analysis. From terrestrial surveys or in-situ GPS stations. From morphological analysis. Derived from the steep front and/or the lateral margins.

| Num | Rock glacier | Thickness [m] | Slope angle [°] | Creep rate [ma⁻¹] | Reference |
|-----|--------------|---------------|----------------|-------------------|------------|
| 1   | Dirru        | 15ᵃᵇᶜ       | 27             | 5.50              | Cicoira et al. (2019)ᵇᶜ   |
| 2   | Furgwanghorn 5 | 15ᵃ         | 28             | 2.90              | Buchli et al. (2018)ᵃ       |
| 3   | Furgwanghorn 7 | 17ᵃ          | 20             | 5.20              | Buchli et al. (2018)ᵃ       |
| 4   | Guggla       | 17ᵇᶜ         | 22             | 4.00              | Delaloye, pers. com., (2020) |
| 5   | HuHH1        | 17ᵇᶜ         | 21             | 1.00              | Müller et al. (2016)ᵇᶜ     |
| 6   | HuHH3        | 20ᵇ           | 22             | 1.70              | Müller et al. (2016)ᵇᶜ     |
| 7   | Kaiserberg   | 27ᵇ           | 9              | 0.50              | Hausman et al. (2012)ᵇᶜ    |
| 8   | Las Liebres  | 25ᵇ           | 15             | 1.10              | Monnier and Kinnard (2016)ᶜ |
| 9   | Laurichard   | 20ᵇ           | 20             | 1.00              | Bodin et al. (2018)ᵇᶜ      |
| 10  | Lazaun       | 25ᵃ           | 15             | 1.20              | Krainer et al. (2015)ᵇᶜ    |
| 11  | Andes #1     | 22ᵃ           | 9              | 0.07              | Arenson (per. com. 2020)ᵃ   |
| 12  | Andes #2     | 18ᵇ           | 11             | 0.05              | Arenson (per. com. 2020)ᵇ   |
| 13  | Andes #3     | 12ᵃ           | 13             | 0.23              | Arenson (per. com. 2020)ᵃ   |
| 14  | Andes #4     | 22ᵃ           | 11             | 0.14              | Arenson (per. com. 2020)ᵃ   |
| 15  | Andes #5     | 14ᵃ           | 8              | 0.01              | Arenson (per. com. 2020)ᵃ   |
| 16  | Muragl 3     | 15ᵃ           | 18             | 1.40              | Arenson (per. com. 2020)ᵃ   |
| 17  | Muragl 4     | 16ᵃ           | 18             | 1.20              | Arenson (per. com. 2020)ᵃ   |
| 18  | Murtél       | 29ᵃ           | 12             | 0.10              | Arenson (per. com. 2020)ᵃ   |
| 19  | Ölgrube      | 31ᵇ           | 13             | 1.10              | Hausmann et al. (2012)ᵇᶜ    |
| 20  | Pierre Brune 1 | 15ᵃᵇ         | 25             | 6.00              | Marcer (pers. com. 2019)ᵇᶜ  |
| 21  | Pierre Brune 2 | 23ᵃᵇ         | 16             | 1.00              | Marcer (pers. com. 2019)ᵇᶜ  |
| 22  | Reichenkar   | 23ᵇ           | 13             | 2.50              | Hausmann et al. (2007)ᵇᶜ    |
| 23  | Rittigraben  | 20ᵃ           | 20             | 1.50              | Kenner et al. (2017)ᵇᶜ     |
| 24  | Schaflberg 1 | 14ᵃ           | 23             | 0.03              | Arenson et al. (2002)ᵇᶜ     |
| 25  | Schaflberg 1 | 25ᵃ           | 16             | 0.20              | Arenson et al. (2002)ᵇᶜ     |
| 26  | Steintälli  | 27ᶜ           | 12             | 0.40              | Delaloye (pers. com. 2020)ᶜ   |
| 27  | Tsarmine     | 17ᶜ           | 22             | 6.00              | Delaloye (pers. com. 2020)ᶜ   |
| 28  | Valdallacqua | 22ᵃ           | 15             | 1.00              | Cicoira (unpublished 2019)ᵇᶜ |

### TABLE 2  Dataset used for the analysis of rock glacier creep at the regional scale comprising observations of creep rates and surface slope angle. From aerial imagery (Satellites or UAVs). Feature tracking analysis. From InSar analysis. From terrestrial surveys or in-situ GPS stations.

| Count | Rock glaciers | Reference |
|-------|---------------|-----------|
| 324   | French inventoryᵃ | Marcer et al. (2019)ᵇᶜ   |
| 30    | Kaunertal inventoryᵃ | Groh and Blöthe (2019)ᵇᶜ |
| 17    | Permosᵇᶜ        | PERMOS (2019)ᵇᶜ           |
| 15    | University of Fribourgᵃᵇᶜ | Delaloye (pers. com. 2020)ᵇᶜ |
| 28    | Present studyᵃᵇᶜ | Tab.1 |

### TABLE 3  Dataset used for the analysis of rock glacier creep at the local scale.

| Rock glacier | Data source (velocity, thickness) | Reference and availability |
|--------------|----------------------------------|---------------------------|
| Laurichard   | TLS, GPR                         | Bodin et al. (2018)ᵇᶜ     |
| Dirru        | UAVs, ERT                        | Cicoira et al. (2019)ᵇᶜ   |
| Pierre Brune | UAVs, ERT                        | Marcer et al. (2020)ᵇᶜ    |
REFERENCES

1. Cicoira A, Beutel J, Faillettaz J, Vieli A. Water controls the seasonal rhythm of rock glacier flow. *Earth and Planetary Science Letters* 2019b; 528: 115844. doi: https://doi.org/10.1016/j.epsl.2019.115844

2. Buchli T, Kos A, Limpach P, Merz K, Zhou X, Springman SM. Kinematic investigations on the Furggwanghorn Rock Glacier, Switzerland. *Permafrost and Periglacial Processes* 2018; 29(1): 3–20.

3. Müller J, Vieli A, Gärtner-Roer I. Rock glaciers on the run – understanding rock glacier landform evolution and recent changes from numerical flow modeling. *The Cryosphere* 2016; 10(6): 2865–2886. doi: 10.5194/tc-10-2865-2016

4. Hausmann H, Krainer K, Brückl E, Ullrich C. Internal structure, ice content and dynamics of Ölgube and Kaiserberg rock glaciers (Ötztal Alps, Austria) determined from geophysical surveys. *Austrian Journal of Earth Sciences* 2012(105): 12-31.

5. Monnier S, Kinnard C. Interrogating the time and processes of development of the Las Liebres rock glacier, central Chilean Andes, using a numerical flow model. *Earth Surface Processes and Landforms* 2016; 41(13): 1884-1893. doi: 10.1002/esp.3956

6. Bodin X, Thibert E, Sanchez O, Rabatel A, Jaillot S. Multi-Annual Kinematics of an Active Rock Glacier Quantified from Very High-Resolution DEMs: An Application-Case in the French Alps. *Remote Sensing* 2018; 10: 547. doi: 10.3390/rs10040547

7. Krainer K, Bressan D, Dietre B, et al. A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy). *Quaternary Research* 2015; 83: 324-335. doi: 10.1016/j.yqres.2014.12.005

8. Krainer K, Bressan D, Dietre B, et al. A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy). *Quaternary Research* 2015; 83: 324-335. doi: 10.1016/j.yqres.2014.12.005

9. Arenson LU, Hoelzle M, Springman S. Borehole deformation measurements and internal structure of some rock glaciers in Switzerland. *Permafrost and Periglacial Processes* 2002; 13(2): 117–135. doi: 10.1002/ppp.414

10. Hausmann H, Krainer K, Brückl E, Mostler W. Internal structure and ice content of Reichenkar rock glacier (Stubai Alps, Austria) assessed by geophysical investigations. *Permafrost and Periglacial Processes* 2007; 18(4): 351-367. doi: 10.1002/ppp.601

11. Kenner R, Phillips M, Beutel J, et al. Factors Controlling Velocity Variations at Short-Term, Seasonal and Multiyear Time Scales, Ritigraben Rock Glacier, Western Swiss Alps. *Permafrost and Periglacial Processes* 2017; 28(4): 675–684. PPP-16-0044.R2 doi: 10.1002/ppp.1953

12. Delaloye R. pers. com. 2020.

13. Marcer M, Serrano C, Brenning A, Bodin X, Goetz J, Schoeneich P. Evaluating the destabilization susceptibility of active rock glaciers in the French Alps. *The Cryosphere* 2019; 13(1): 141–155. doi: 10.5194/tc-13-141-2019

14. Groh T, Blöthe JH. Rock Glacier Kinematics in the Kaunertal, Ötztal Alps, Austria. *Geosciences* 2019; 9(9). doi: 10.3390/geosciences9090373

15. PERMOS. Permafrost in Switzerland 2014/2015 to 2017/2018. Noetzli, J., Pellet, C., and Staub, B. (eds.), Glaciological Report (Permafrost) No. 16-19. tech. rep., the Cryospheric commission of the Swiss Academy of Sciences, 104 pp.; 2019.

16. Marcer M, Cicoira A, Bodin X, Schoeneich P. Rock glacier destabilization due to climate change. *Nature Communications* submitted.