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Retrospective

A tribute to Louis (1952): On the theory of glacial erosion in valleys

Pierre G. Valla

Institute of Earth Sciences (ISTerre), Université Grenoble Alps, Université Savoie Mont Blanc, CNRS, IRD, IFSTAR, 38000 Grenoble, France

Correspondence: Pierre G. Valla (pierre.valla@univ-grenoble-alpes.fr)

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The scientific contribution of Herbert Louis (1952) focuses on glacial erosion and the development of glacial landscapes, and in this it nicely follows the expansion of scientific research on glacial geomorphology at the beginning of the 20th century. Pioneering work by Penck (1905) and De Martonne (1910) had already emphasized the importance of glacial topographic shaping at the Earth's surface, especially in high-latitude or high-elevation mountainous areas. In addition, glaciologists and glacial geomorphologists had already recognized at that time the profound topographic differences between ice-sheet (referred to as "regional-scale glaciation") and valley/alpine glacier (referred to as "local-scale glaciation") landscapes. Interestingly, the influence of initial (i.e., pre-glacial) relief and substrate (i.e., lithology, bedrock fracturing) on magnitudes and patterns of erosion has already been emphasized for valley glaciers, whereas it was thought to have had only little influence on the erosion dynamics of ice sheets.

At the time of Louis' (1952) contribution, large geomorphic evidence had been reported for the impact of valley glaciers on mountainous landscapes, with various case studies of observed specific and conspicuous features. However, there was no scientific consensus on the physical basis/theory for glacial erosion, with remaining active discussion within the community. One striking example of such debate is the occurrence and origin of steps and basins along glacial valleys (Lewis, 1947; Louis, 1952) and the widespread observations of U-shaped valley cross-sections (referred to as "trough valleys"). Glacial valley steps and basins have been proposed to have several possible origins, with enhanced ice flux at tributary confluences (e.g., Penck, 1905), the role of lithological spatial variations or the proposed view by some scientists that glacial valleys are bedforms of ice streams (i.e., a general term at the time for describing any body of moving ice). It is interesting to note that these hypotheses have been recently quantitatively assessed using numerical glacial modeling, showing a major impact of ice-flux increase at tributary junctions for glacial steps and basin development along the valley longitudinal profile (MacGregor et al., 2000), as well as the topographic influence on ice-stream dynamics (i.e., topographically constrained corridors of fast ice flow within ice sheets, e.g., Kessler et al., 2008). However, as also noted by Louis (1952) and others previously, not all observed glacial valley steps or basins can be linked to these proposed controlling factors. Pre-glacial relief inheritance has been suggested as an alternative hypothesis for these glacial features (De Martonne, 1910), and this point of view was actually also taken by Louis (1952). The importance of pre-glacial relief inheritance for glacial dynamics and topographic valley evolution is another important factor, which has also been highlighted recently using numerical modeling (e.g., Pedersen and Egholm, 2013).

The overall aim of Louis (1952) at the time had been to propose a physical interpretation of these widely observed glacial landscape features, building his hypothesis on field observations since no consensus on any physical basis for glacial erosion was present at that time. One major issue exposed in his contribution was that previously proposed explanations considered the erosive action of valley glaciers in the view of a viscous fluid with almost laminar flow. However, such glacier behavior would go against the presence of inherited steps in glacial valleys, which in the case of laminar flow should be erased by the glacier's action following ice acceleration at the glacial topographic step. Although the logical reasoning appears interesting and correct, it relies on a static view of glacier dynamics with the inheritance hypothesis for glacial valley steps, whereas more recent research has shown that these glacial features can emerge from internal glacier dynamics when considering small-scale subglacial processes (e.g., Anderson, 2014), subglacial hydrology and sediment transport (e.g., Herman et al., 2011) over long-term repetitive glaciations. However, Louis (1952) based his reasoning not only on observed glacial features but also on laboratory experiments which suggested that ice viscosity cannot be considered constant but rather changes with stress ratios, temperature or crystal orientation (Glen, 1955). As a consequence, Louis (1952) joined previously proposed hypotheses that rather considered the flow of a valley glacier as more similar to a plastic behavior, with which a critical stress is associated. Such behavior was later shown to be applicable under specific conditions to describe a valley glacier's height, length and longitudinal profile (Cuffey and Paterson, 2010).

With these observations and considerations, Louis (1952) proposed a physical theory for valley glacier flow and its erosional impact on bedrock in the view of the "block floe movement" (Fig. 1 in Louis, 1952), which is a block movement of a rigid ice mass that can break in specific parts along floes (e.g., seracs). Such valley glacier behavior would be, in the view of Louis (1952), compatible with the observation that the cross-section of the valley glacier does not necessarily change at topographic steps (which would be expected in the case of viscous fluid behavior) and that high friction within the ice itself would allow more plastic behavior in the longitudinal than in the transverse direction. Louis (1952) proposed a schematic view of individual rigid ice bodies that are pushing over an inclined (pre-glacial topographic inheritance) bedrock surface in response to gravity. By illustrating the force balance and spatial variations between ice rigid bodies, he proposed a transfer of basal pressure on the inclined bedrock surface as a driver for bedrock glacial erosion. This simple physical basis was appealing at that time, although not entirely physically based on subglacial processes as developed afterwards (Hallet, 1979), since this allowed the explanation of first-order glacial landscape features such as valley glacier steps and flats. Upstream of any topographic step, the reduction in effective pressure above the steepening of the topographic surface (resulting from ice thinning) would lead to minor erosional efficiency of the glacier, in concordance with specific glacial features such as "cirque sills". In addition, the increased bedrock stresses at the foot of topographic steps may favor basin development, in line with cirque creation or overdeepenings frequently encountered in alpine landscapes. Louis (1952) noted that glacial cirques and overdeepenings can be of only limited extent, since the bedrock counterslope would induce increased friction and thus reduced erosion, in agreement with the most recent views on the evolution of overdeepenings although the proposed processes differ with subglacial water and sediments involved (Cook and Swift, 2012). Finally, Louis (1952) also considered the possibility that valley glaciers can flow over a sediment/soil layer (i.e., soft-bed glacier dynamics) that he described as a "plastic intermediate zone" and to which his theoretical basis also applied. It is worth noting, however, that the proposed physical theory by Louis (1952) had been mainly justified, as explicitly expressed by himself in his contribution, to explain "aggravation of pre-existing irregularities of slope", i.e., landscape features in the longitudinal profile such as valley steps, flats and basins. In this line of thought, the "rigid block floe movement" theory allowed Louis (1952) to satisfactorily explain the variety of observed morphologies in glacial landscapes, giving at least some credit to it. One final observation that favored the rigid block theory of Louis (1952) at the time was the low variability in ice velocity from surface to bottom measurements. However, the reported observations at that time may have been recorded for a specific warm-based glacier where the ice flow would be dominated by basal sliding with respect to internal ice deformation. It is interesting to note that Louis (1952) partly envisaged the role of subglacial water in basal sliding in his contribution, referring to a valley glacier that "sits on a kind of lubricant".

After stating his theoretical hypothesis, Louis (1952) adopted a more consensual and intermediate position where he considered that the physical behavior of a valley glacier would lie between a viscous fluid and a flow of rigid individual bodies. In his view, the block floe movement hypothesis is most certainly not physically correct to describe the ice flow of valley glaciers, which can adopt end-member behaviors depending on several factors including topographic conditions. For him, the merit of his proposed physical theory was to open new directions and to raise questions for a better understanding of the variability in valley glaciers. In his view, the rigid behavior of the ice would be of prime importance for erosion dynamics and the evolution of glacial landscapes. He then posed the question of the observed variability in valley glacier behaviors as well as the diversity of observed glacial landscapes, which for him evidences contrasting erosional efficiency of valley glaciers in sculpting their bedrock. He phrased this as an open question, and this is still a matter of debate and active scientific research today (e.g., Herman et al., 2021). The proposed intermediate and compromise view of Louis (1952) concerning the flow of a valley glacier may also reflect the general thinking of the time within the scientific community, with the major achievement of Glen's law of non-linear viscous flow for glaciers and ice sheets, which was physically demonstrated a few years afterwards (Glen, 1955).

Another merit and interesting aspect of Louis' (1952) contribution was his conceptual investigation of the transverse profile of valley glaciers. In the final part of his contribution, he explored how important the varying contact pressure of flowing ice to the underlying bedrock (in both the ablation and the accumulation areas) might be and how this effect may partly explain the development of U-shaped glacial valleys with respect to the relative contribution of inherited pre-glacial relief features. He also raised a first-order question for the development of U-shaped valley morphology (Harbor, 1992), questioning whether this results from enhanced vertical or horizontal glacial erosion. In the view of Louis (1952), both situations can occur along a glacial valley profile and would depend on specific topographic conditions (i.e., the occurrence of longitudinal steps in a glacial profile). Finally, he developed his reasoning based on some key morphological observations (Figs. 2 and 3 in Louis, 1952) for the upper part of a glacier valley cross-section, above the U-shaped deeper part (referred to as the "valley trough"). This work is, to my knowledge, very specific and insightful, since the landforms around the glacial altitudinal limit ("trimline" as already exposed by Penck, 1905) have received only minor attention since then. For Louis (1952), the glacial landforms above the U-shaped valley part can be differentiated between steep slopes below the trimline (*Schliffkehle*) and subsequent low-slope areas (*Schliffbord*). Following Louis' (1952) view on inherited pre-glacial relief, such landforms may indicate the magnitude of lateral glacial erosion at the upper boundary (i.e., lateral margin of the valley glacier), which is emphasized at depth within the trough valley (U-shaped section of the valley transverse profile). These observations also raised the question of the geomorphological significance of the trimline as the topographic boundary for either the glacier maximum vertical extent or efficient glacial erosion, a point also recently raised by numerical studies of alpine glacier modeling (e.g., Seguinot et al., 2018).

Finally, Louis (1952) discussed the significance of the relatively low slope shoulder areas which are located above the U-shaped valley part (*Trogschulter*) as being either the result of lateral erosion by the glacier at high elevations or the inherited features from "over-printed old valley floor remnants". In his view, this question is not simple and the origin of glacial valley shoulders depends on both the initial topographic configuration (pre-glacial relief) and the differences in topographic slopes between the ridgelines (periglacial area) and the valley flanks (glacial area). In addition, he pointed to the need for a pronounced vertical structure (high total relief) for observing developed valley shoulders along glacial valley profiles. The question of pre-glacial inheritance vs. glacial erosional imprint for the occurrence of low-slope, high-elevation glacial shoulders or plateaux has been an important research topic in fjord environments, and their existence in alpine areas is also the subject of discussion. However, investigating the transition from glacial to periglacial landforms around the trimline has remained challenging, since several geomorphic processes are acting at these sites and may vary in both space (i.e., along the valley glacier longitudinal profile) and time (i.e., over repetitive glacial periods or within the course of an individual glacial cycle).

In summary, the reported observations and proposed physical explanations for glacial erosion and landscape features by Louis (1952) have the important merit of synthesizing key morphological evidence of glacier dynamics and of proposing a conceptual model for landscape evolution under glacier erosional imprint. Most of the concepts and proposed controlling factors of glacial erosion are still valid at present, although the implied physical subglacial processes and associated theoretical basis for glacial erosion have evolved substantially since Louis' (1952) contribution. Some important aspects of glacial landscapes still have to be investigated: (1) the relative importance of vertical vs. lateral glacial erosion for the valley cross-profile evolution and (2) the possible controlling mechanism(s) for the observed contrast and diversity of glacial landforms at high elevations, i.e., the contact between the glacially modified trough below the trimline with the frost-shattered terrain above it.

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