

Paraglacial Geomorphology

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Part 1: What is Paraglacial Geomorphology?

The paraglacial concept was defined in by Church and Ryder (1972) as “nonglacial processes that are directly conditioned by glaciation, (including) both proglacial processes, and to those occurring around and within the margins of a former glacier that are the direct result of the former presence of ice” (p.3059). Since then, the term *paraglacial* has shifted away from being defined by geomorphic processes and instead come to represent conditions of accelerated geomorphological activity that follow glacial climates.

“A unifying attribute of all forms of paraglacial response is that deglaciation results in the exposure of unstable or metastable sediment sources that are subsequently tapped by a wide variety of processes over a wide range of timescales” (Ballantyne, 2002b, p. 327). The Church and Ryder definition of *paraglacial period* (see fig.1) refers to the period of time in which paraglacial processes occur, and is further qualified as a ‘readjustment’ period as glacial systems “relax towards a nonglacial state” (Ballantyne, 2002, p.2937).

The spread and retreat of ice sheets during glacial climates has a tremendous impact on its environment. Newly exposed landscapes are often unstable and therefore susceptible to accelerated rates of change. Paraglacial geomorphology is the area of study that focuses on “earth-surface processes, sediments, landforms, landsystems and landscapes that are directly conditioned by former glaciation and deglaciation” (Ballantyne , 2002, p.1937). These processes are the means by which glacial conditions transition to nonglacial conditions. They represent a time of landscape readjustment, as glacial sediment is reworked and landsurfaces react to the retreat of glacial ice.

The tremendous weight of glacial ice provides a pressure force strong enough to depress the underlying earth surface. Bedrock under the load of glacial ice has a slow viscous response,

meaning that the period of rebound during unloading can last for thousands of years following the melting of the ice (Ruddiman, 2008). While the Ballantyne article qualifies that glacio-isostatic rebound is not an earth-surface process, but rather an indirect tectonic response, it also states that “glacio-isostatic uplift may influence various paraglacial processes, notably (the) incision of valley fills and marine deltas” (p.1938) (see fig.2).

Debris produced by ice sheets ranges from the finest of clays to large boulders, all of which are carried and deposited along the margins of the sheet when it begins to melt. Rates of erosion and sediment transport associated with retreating glaciers far exceed their background rates. Sediment transport rates are further increased by the enormous volume of water released by melting glacial ice.

Ballantyne (2002) identifies six paraglacial landsystems; rock slopes, drift-mantled slopes, glacier forelands, and alluvial, lacustrine and coastal systems based on their locational context and subdivided “according to a range of nonuniform criteria” (p.2001). Rock slope systems (see Section 2), are subdivided by mode of failure.

Primary paraglacial systems are those in which the sediment that is released has been directly glacially conditioned. For example, a rock slope failure due to deglacial stress-release would be considered a primary system. “Secondary paraglacial systems are those in which rates of sediment yield are conditioned not only by release of *in situ* glacial sediment but also by reworking of paraglacial sediment stores such as talus, debris cones, alluvial fans and valley fills in upland tributary valleys” (Ballantyne, 2002b, p. 373.).

The following section considers paraglacial processes in the context of rock slope adjustment to deglaciation.

Part 2: Rock Slopes

Ballantyne (2002) asserts that “one of the most important geomorphological consequences of deglaciation in mountain environments is the exposure of glacially steepened rockwalls” (p.1938). He notes three particular modes of response to instability in rock slope systems that will be further discussed in detail to follow. A catastrophic slope failure can occur in the form of rock avalanches or major slide events. Large-scale deformation of the rock mass (rock mass creep) may occur, although this too can lead to a catastrophic failure of the slope. Frequent rockfall events may occur due to the rapid adjustment of rock faces and accumulate as talus debris at the slope foot.

Paraglacial processes promote instability in rock slopes by redistributing stress forces. Internal stress adjustments occur within the rock mass from erosional processes, while the compressional stresses imposed on the valley floor and walls by the load of the ice mass are released during deglacial unloading.

Paraglacial rock slopes may be steepened by accelerated rates of erosion, resulting in deeper troughs, higher rock faces and increased overburden. These processes may be further pronounced in mountainous terrain which may experience concentrations of ice flow along glacial troughs, or in regions with scarp slopes that affect the movement of the ice sheet’s basal layers. This causes an increase in the shear stresses that act within the rock mass, and exposes potential failure planes near the slope foot. “These effects may generate tensile stress conditions... and promote rock-slope failure along pre-existing joint sets or other planes of weakness during or after ice retreat” (Ballantyne, 2002, p. 1939)”.

The stability of rock slopes in paraglacial environments is further compromised by stress-release resulting from debuitressing, when the support of adjacent ice is removed during

glacial retreat. This can impact the stress distribution of the slope, and lead to building tensile stresses. Additionally, as the overlying load of ice is lessened, the rebounding bedrock will begin to release strain energy associated with unloading. This rebound promotes jointing, loss of cohesion within the rock mass and a general relaxation of internal stresses. Instability may be further increased by associated increases in joint-water pressure and stress redistribution.

Slope Failure

Rock slopes in such unstable conditions may result in a large scale failure or collapse of the slope. Ballantyne (2002) notes that “failure due to glacial thinning and debuttreassing affects not only the walls of glacier troughs, but also cirque headwalls and other rockwall source areas” (p.1940). Additional studies by Evans and Clague (1988, 1994) suggest that in alpine locations with ice-filled cirques, catastrophic rock failure is actually characteristic to the location and not a paraglacial process (p.1941).

A study of eight paraglacial rock slope failures in northwest England (Wilson and Smith, 2006) classified failures according to the geomorphological characteristics of the sites. The classifications included rockslides, deformation by rock mass creep or reverse faulting, and compound failures for those which showed characteristics of both deformation and sliding (p. 241). Their analysis of these failures states that the sites “show no signs of having been modified by the passage of glacier ice and it is inferred that they post-date the (Last Glacial Maximum)... effects of glaciation and deglaciation were probably of critical importance in weakening the slopes, through the readjustment of slope stresses, and ultimately in causing failure...thus, are regarded as paraglacial phenomena” (p. 249).

Rock Mass Creep

Ballantyne notes the convincing evidence of a causal relationship between glacial debuttrressing and rock mass creep. By this process, the subsurface of these rock slopes may be subject slow deformation that “may be a major factor in reducing rock slopes to a state of critical conditional instability, and is this sometimes a precursor of catastrophic failure” (Ballantyne 2000, p.1943)”.

Typical characteristics of rock mass creep include wide fractures, antiscarps, elongated ridge-top deepressions and collapse pits (Ballantyne 2000, p.1943). These features indicate tensile stress and movement in nearsurface zone. This movement is a response to gravitational forces only. Similarly to soil creep, the rock mass is not under continuous external stress, but rather a loss of cohesion and frictional resistance cause it to move under gravity (Ritter et al, 2006, p.102). The elastic and viscous properties of the bedrock by which it deformed under loading of glacial ice are also responsible for this rebound process. Removal of lateral support contributes to the gravitationally induced tensile stresses.

Creep is often seen as a precursor process to greater mass movements. Studies on rock mass creep in British Columbia describe observed opening of tension cracks in a rock mass. This was suggestive of glacial debuttrressing of lower slopes, subsequently initiating or renewing slope movement.

Rockfalls

Oversteepened slopes may respond to deglaciation with rockfall activity. When this happens, talus accumulations result below the area of the falls. The rate/frequency of these rockfalls is initially high, and deteriorates over time. “Undercutting of the rock or soil face by erosive agents acting at the base of the material accelerates the process” (Ritter et al, p.105).

Loss of lateral support increases tension and may result in overhangs which encourage incipient cracking. Unlike creep, rockfalls occur as discrete events of a freely falling body.

Studies of talus accumulations have revealed that similar accelerated rockfall activity may in fact “reflect Lateglacial periglacial conditions (particularly enhanced freeze-thaw activity) as well as intrinsic paraglacial rockwall instability” (Ballantyne, 1990, p.1946).

Rockwall retreat in both types of environments can be difficult to distinguish from one another (see fig.3).

Studies of talus accumulation on recently deglaciated terrain do indeed indicate enhanced paraglacial rockfall activity following glacial debuttressing of rockwalls. However, some uncertainty remains in distinguishing the stress-releasing influences of freeze-thaw cycling on Lateglacial rockwalls from those of paraglacial debuttressing activity.

Part 3: Paraglacial Geomorphology and Time

Ballantyne discusses a lingering debate over the definition of the paraglacial concept. Ultimately, it seems to stem from the open-ended timescale of paraglacial processes. Generalizations about the spatial and temporal scales of paraglacial processes have led to some confusion over the suitability of the paraglacial definition.

The great range of processes and timescales associated with deglaciation make a clear quantifiable definition difficult to establish. “The duration of the period of paraglacial activity varies over several orders of magnitude, from 10–100 years for small-scale modification of glacier forelands to >10,000 years for rock-slope failure” (Ballantyne, 2002, p. 2000).

The only element common to the many different forms of response discussed by Ballantyne is the effect of deglaciation on the “exposure of unstable or metastable sediment

stores that are subsequently tapped over a wide range of timescales by a wide range of processes” (Ballantyne, 2002, p.1994). The ‘paraglacial period’ can then be seen as “the timescale over which such a sediment store is either exhausted or attains stability in relation to particular reworking processes” (p.1994). Ballantyne suggests that ‘paraglacial period’ as well as paraglacial systems and processes should be conceptualized in terms of glacially conditioned sediment availability.

Paraglacial sediment yield seems to be most significantly influenced by glacio-isostatic uplift. “Where glacio-isostatic uplift results in falling base levels, there may be rejuvenation of paraglacial sediment reworking as streams cut down into both in situ glacial deposits and paraglacial sediment stores” (p. 1999).

With sediment yield established as the defining feature of paraglacial time, this can further illustrate the contrast between primary and secondary paraglacial systems. “If it is assumed that glacially conditioned sediment availability represents the unifying attribute of paraglacial sediment reworking, the decline in the rate of primary paraglacial sediment reworking can be approximated by a sediment exhaustion model” (Ballantyne 2002, p. 1994) (see fig.4). Following general assumptions regarding supply-limited transport of sediment, the model describes the reduction of sediment transport either by increased stability or by removal of the sediment.

In larger secondary paraglacial systems, “sediment yield is conditioned not only by the supply of in situ glacial sediment, but also by re-entrainment of sediment previously reworked during the period of primary paraglacial activity (Ballantyne 2002, p. 1995).” An example given of this is reworking is the entrenchment of paraglacial alluvial fans and paraglacial valley fills by trunk streams. Modeling these larger, more complex systems can

prove to be more difficult. One model presented for these systems operates on an observed positive relationship between specific sediment yield and catchment size in larger basins.

Another model discussed used the same concept of exhaustion as primary systems. The potential of each model has valid support, and Ballantyne notes the possibility that they each represent end points of a continuum of possibilities (p.1998).

Many larger systems, particularly fluvial systems “are likely to experience enhanced sediment input and hence carry enhanced sediment loads in the period immediately following deglaciation, the development of a later peak in sediment yield... may be regarded as a form of complex response” (Ballantyne, 2002, p. 1998).

All models are vulnerable to extrinsic influences such as changes in climate or anthropogenic activity. These factors may extend or even rejuvenate paraglacial reworking of sediment, and so the difficulty remains in quantifying discrete time periods of paraglacial activity. “Even in contexts where a discrete initial ‘paraglacial period’ can be indentified, extrinsic perturbation may remobilise glacigenic sediment long after the termination of the initial period of paraglacial landscape adjustment” (Ballantyne, 2002, p. 2001). The temporal pattern of paraglacial sediment release therefore remains susceptible to extrinsic disturbances and thus the rejuvenation of paraglacial reworking remains a possibility in postglacial climates well after the termination of the initial period of paraglacial response.

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