Journal of Glaciology, Vol. 35, No. 121, 1989

EARLY DISCOVERERS XXXVI

W.J. McGEE ON GLACIAL EROSION LAWS AND THE DEVELOPMENT OF GLACIAL VALLEYS

By JONATHAN M. HARBOR

(Department of Geological Sciences and Quaternary Research Center, University of Washington,

AJ-20, Seattle, Washington 98195, U.S.A.)

ABSTRACT. In work presented in 1883 and published in full in 1894, W.J. McGee made one of the first clear attempts to outline the main morphologic differences between glaciated valleys and valleys developed by processes dominant in more temperate areas. Moreover, with an unprecedented analysis of glacial erosion, he attempted for the first time to explain the evolution of glacial land forms in terms of theoretical predictions of patterns of erosion under valley glaciers. In the latter half of the nineteenth century, there was fierce debate over whether glaciers were even capable of significant erosion, so it is perhaps not surprising that McGee's analysis of glacial erosion processes and land-form development received little attention in his own time. Despite this, McGee's work provided some of the first really convincing glacial explanations for the development of land forms such as hanging valleys and U-shaped valleys, and these were developed more fully in later work by Davis (1900) and Gilbert (1903). In modern research, the use of theoretical erosion laws and a knowledge of ice dynamics to develop models of land-form development is emerging as a major theme in glacial geomorphology, marking a return to the methodology pioneered by W.J. McGee.

OVERVIEW

By the latter part of the nineteenth century the concept of continental glaciation championed by Louis Agassiz was widely accepted as the most satisfactory explanation for the widespread occurrence of diamictons and erratics in the northern parts of Europe and North America (Hallam, 1983). Glacial geologists were actively involved in classifying glacial deposits and tracing the limits of former ice sheets (e.g. Chamberlin, 1895; Geikie, 1895), while glaciologists such as Forbes (1843, 1859) and Tyndall (1860, 1872) had noted that glaciers slide over their beds, and were explaining measured horizontal and vertical displacement profiles for glaciers in terms of a viscous model for ice flow. The basic processes of glacial erosion had been outlined by Tyndall (1864, p. 265):

> "In the case of every glacier we have two agents at work — the ice exerting a crushing force on every point of the bed which bears its weight, and either rasping this point into powder or tearing it bodily from the rock to which it belongs; while the water which everywhere accumulates upon the bed of the glacier continually washes the detritus away, and leaves the rock clean for further abrasion .... But the glacier does more than abrade. Rocks are not homogeneous; they are intersected by joints and places of weakness, which divide them into virtually detached masses. A glacier is undoubtedly competent to root such masses bodily away."

Although it had long been recognized that glaciers abraded rock surfaces to produce striae and grooves, and large-scale deposition was relatively well accepted, the erosive power of glaciers and their ability to modify substantially the landscape was a topic of heated debate. Following A.C. Ramsay's (1859, p. 403) initial bold assertion "that all glaciers must deepen their bed by erosion", Tyndall (1862) argued that alpine valleys were *solely* the product of glacial erosion. The more general view was that alpine valleys originated as river valleys, which were subsequently modified to some degree by glacial erosion (e.g. Ramsay, 1862b), but whether this glacial modification was purely superficial, or if it was largely responsible for the shape and great depth of some valleys, was the basis for a long-lived dispute between Ramsay (1864, 1876), Judd (1876), Bonney (1871, 1874), and Irving (1883), among others. In fact, the significance of glacial erosion in the development of major land forms was still doubted by several influential geologists well into the twentieth century (e.g. Bonney, 1910; Garwood, 1910) although, as Davies (1969, p. 309) has argued, by the 1880s it was generally accepted that glaciers were capable of significant erosion.

In a presentation in 1883 and a paper in 1894, W.J. McGee provided one of the first detailed descriptions of the distinctive characteristics of glaciated valleys (see also LeConte, 1873):

> "Glacial cañons are characterized by several peculiar features: 1. They are U shaped rather than V shaped in cross-profile; 2. Small tributary gorges usually enter at levels considerably above the cañon-bottoms; 3. In longitudinal profile the cañon-bottoms are irregularly terraced — i.e., made up of a series of rude steps in variable form and dimensions, — and some of the terraces are so deeply excavated as to form rock-basins occupied by lakelets; 4. The cañons are sometimes locally expanded into amphitheaters; 5. The cañon-bottom is not always obdurate rock, but many consist of coarse fragmental debris in which individual blocks are deeply striated and as smoothly polished as are most solid ledges, though they may rest so insecurely in their positions that a hand can overthrow them; and 6. The volume of glacial debris in moraine and valley deposits is but a small fraction of the cubic content of the cañon from which it was derived" (McGee, 1894, p. 351).

Not content simply to describe the form of the landscape, McGee tried to explain the development of these features in terms of patterns of glacier flow and glacial erosion, and in

https://doi.org/10.3189/S0022143000009357 Published online by Cambridge University Press

fact went on to use land-form development as a means to assess the relative merits of a number of glacial erosion laws that he proposed. However, neither the initial paper presented for McGee by W. Upham at the annual meeting of the American Association for the Advancement of Science in 1883, nor the full paper (McGee, 1894) were well received. A commentator reporting discussion of the original presentation of McGee's work noted that:

"The general expression was to the effect that the theory had been framed without sufficient observation of the facts, and that, if the author had taken the trouble to see and examine various cañons, he would have come to a widely different set of conclusions" (Anonymous, 1883, p. 316).

The only detailed comment on McGee's work I have been able to find is similarly unenthusiastic:

"We may hope that, just as Gilbert and others have worked out the principles of water-erosion, so the much more difficult problem of ice-erosion may some day be reduced to analysis. An attempt in this direction has been made by McGee in a paper on "Glacial Cañons" ... .
[Glacial landforms provide] the tests by which any synthetic theory of the mechanisms of ice-erosion must be tried, but such a theory is ... still a desideratum. McGee's treatment of the problem ... labours under the drawback that it too often involves conflicting elements, the relative value of which is a matter of uncertainty" (Harker, 1899, p. 1966-99).

From such comments, it is clear that McGee's analysis had relatively little impact on contemporary glacial geomorphologists. This was perhaps because McGee's analysis of geomorphic processes as a way to understand land-form development was not in tune with mainstream geomorphology at the time. In the latter part of the nineteenth century and the early twentieth century, geomorphology was becoming increasingly dominated by evolutionary concepts which stressed deductive models of land-form change over long time spans, in particular Davis' (1884, 1909) "Geographical cycle", rather than analyses of the processes responsible for land-form development. Somewhat later, McGee's explanations for the development of certain specific forms (hanging valleys and U-shaped valleys) were referred to and developed by Davis (1900) and Gilbert (1903), but McGee's more fundamental methodology, the use of erosion laws combined with a knowledge of ice flow to explain erosion patterns and the evolution of land forms, was not to become an important part of glacial geomorphology until well into the latter half of the twentieth century, beginning with Nye and Martin (1968), Johnson (1970), and Boulton (1974). However, in retrospect, McGee's work on glacial land forms and erosion laws contained some important insights and approaches which, although not a part of mainstream glacial geomorphology until almost a century later, represented the first serious attempt to determine glacial erosion laws and test their ability to explain the development of glacial land forms.

W.J. McGEE

William John McGee — or simply W.J. McGee, as he preferred to be known — was born in Farley, Iowa, in 1853. He was largely self-educated, and became interested in glacial phenomena through a familiarity with the topography and geology of his home area. In fact, by the time he joined the United States Geological Survey (USGS) in 1883, he had completed a topographic and geologic survey of almost 12 000 square miles of north-eastern Iowa (Knowlton, 1916). Before joining the USGS he worked briefly in the Sierra Nevada, and it was here that he developed his ideas on glacial canyons. At the USGS he was closely associated with John Wesley Powell and worked on a wide range of topics, including the glaciation of the upper Mississippi Valley and more especially the use of topographic forms in reconstructing landscape chronology. He was in charge of the division of Atlantic Coastal Plain Geology for several years, and was perhaps best known in geology for his reconstruction of the submergence and uplift history of the Middle Atlantic Slope on the basis of topographic forms and basic geological relationships (Chorley and others, 1964). He was a founding member of the Geological Society of America, and served as President of the National Geographic Society in 1904 and 1905.

In 1893, McGee followed Powell to the Bureau of American Ethnology, which allowed McGee to concentrate on various anthropological projects (Darton, 1916), and in 1902 he became the first President of the American Anthropological Association. After taking charge of the Department of Anthropology for the St. Louis Exposition of 1904, he became the first Director of the St. Louis Public Museum (1905–07). In 1907, he was appointed Vice-Chairman of the newly created Inland Waterways Commission, and joined the Bureau of Soils, U.S. Department of Agriculture. He continued in these positions, working mainly on water conservation and soil-erosion problems until his death in 1912 at the Cosmos Club in Washington D.C.*

McGEE'S GLACIAL EROSION LAWS

Observing significant differences in form between glaciated valleys and valleys developed by processes dominant in more temperate areas, McGee realized that to understand why the geometry of a landscape changed as a result of glacial action required that one understand what controlled spatial variations in glacial erosion. This led him to set up a variety of glacial erosion laws which, in combination with an understanding of ice flow in valleys, allowed him to predict spatial patterns of erosion and thus assess how an initial fluvial valley might to expected to evolve under the influence of glacial erosion. With this methodology, McGee not only generated improved explanations for the development of land forms but also, by assessing which erosion laws most successfully predicted the development of observed glacial land forms, provided a way to test the validity of his erosion laws.

Although McGee's prose is hard to interpret in some crucial areas, he appears to have visualized glacial erosion as dependent on three competing elements: *Intensity* (I); *Friction* (F); and *Effectiveness* (E), and he used these elements to generate three equations describing the major controls on glacial erosion rates. In fact, what McGee set up were not really competing measures of erosion, but simply three different ways of attempting to estimate the magnitude of glacial erosion. McGee first defined the intensity (I) of glacial action as:

$$I = wv \quad \text{(McGee, 1894, p. 354)} \qquad (1)$$

where w is the weight, or normal pressure of ice, and v is the "down-stream impulse", or "total potential energy" available in generating movement. Following a suggestion from J.E. Hendricks, a mathematician, McGee set:

$$v = nw\sin(\theta) \quad \text{(McGee, 1894, p. 354)} \qquad (2)$$

where n is "an unknown factor depending on molecular force, and hence involving temperature" (McGee, 1894, p. 354) and θ is the bed slope of the glacier. Although McGee did not explicitly state that he considered v to be the ice-flow velocity, it is possible that this is what he had in mind as he used observed variations in surface velocities as an indication of spatial variations in v across a valley glacier. With v as velocity, McGee's measure of erosion intensity (Equation (1)) represents the total energy expenditure per unit time at a point which, as had been recognized earlier by Moore (1865), should provide a measure of the total energy available for erosion.

With intensity providing a measure of total energy for erosion, on a more detailed scale McGee argued that the actual amount of rock grinding under a glacier could be judged by the friction between the glacier and its bed. As

*The details of McGee's life and work are summarized in a biography by his sister (McGee, 1915) and the records of the McGee memorial meeting of the Washington Academy of Science (Washington Academy of Science, 1916).

McGee could see no clear way to formulate a friction law for the complex ice/bedrock interface, he suggested that the basic law must be some function of w and v, but with an "indeterminate factor of considerable moment" (x). Thus friction (F) was given as:

$$F = f(v)(Wx\cos(\theta)) \quad \text{(McGee, 1894, p. 354)} \qquad (3)$$

where $f(v)$ represents the influence of flow velocity on friction. McGee clearly recognized the complexity of describing friction at a glacier bed where rock fragments may move relative to both ice and bedrock, or ice may overlie a deformable bed:

> "... if detached rock fragments intervene, they will project into the more yielding material and thereby increase the frictional surface; when the slip may ... occur in part on each side of the fragments (i.e., the ice may flow over the fragments, while they themselves move at a slower rate over the valley bottom ...). Also, if a continuous sheet of comminuted debris intervene, the movement may be divided between its upper and lower surfaces; and if the intercalated sheet be thick, several planes of slip may exist within it and its own motion become differential. Again, if fragments ... project into the ice or lie within a differentially moving ground moraine, the unequal flow will most rapidly carry forward their summits, initiate rolling, and thus diminish friction ... " (McGee, 1894, p. 352).

Only in the past few years have deformable beds such as McGee described become a major research interest in glaciology and glacial geomorphology (e.g. Alley and others, 1986; Boulton, 1986; Robin, 1986; Boulton and Hindmarsh, 1987).

Finally, moving on to a detailed consideration of what actually went on at the bed of a glacier to evacuate debris, McGee argued that the effectiveness of glacial erosion is a function of the:

> "... ratio between weight and down-stream impulse; for manifestly, if the weight be in excess, the predominant tendency must ever be to fix and retain in their places all bowlders, pebbles, sandgrains, and smaller particles; when the weight and impulse are as w and v in the diagram (Fig. 1) their resultant will tend to retain rather than remove such fragments ... ; when the factors are equal, as are w' and v', their resultant will tend equally to retain and to remove particles ... ; and when the ratio is as w'' to v'', the disposition will be to overturn and sweep forward all fragments" (McGee, 1894, p. 353).

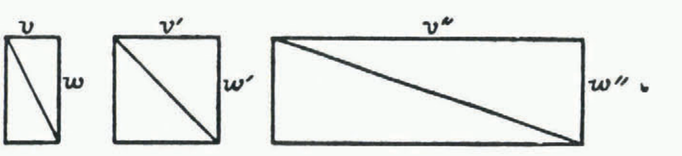

Fig. 1. The influence of the relative magnitude of down-stream impulse (v) and the overlying weight of ice (w) on the tendency of clasts at the base of a glacier to be moved along the bed (McGee, 1894, p. 353).

Thus effectiveness (E) is given by:

$$E = (1 - z)v/w \quad \text{(McGee, 1894, p. 354)} \qquad (4)$$

where z is a variable of unknown magnitude. This depiction of clasts at the bed of a glacier supporting the effective weight of the overlying ice contrasted sharply with Chamberlin's (1888) view that clasts at the bed of a glacier were carried along in deforming ice. In this instance, McGee seemed to view ice almost as a rigid body, whereas to Chamberlin complicated patterns of striations around rock steps indicated that ice was a deforming, flowing fluid.

Interestingly, the idea that clasts at the bed of a glacier support the effective weight of the overlying ice is also a characteristic of Boulton's (1974) relatively recent description of glacial abrasion. In Boulton's model, the rate of abrasion scales with the difference between the effective normal pressure (pressing down on a clast) and the velocity of the clast parallel to the bed, and thus there is a general similarity between the behavior of Boulton's equation for abrasion and McGee's measure of erosion effectiveness. In contrast, the recent model of glacial abrasion proposed by Hallet (1979) appeals to Chamberlin's view that clasts essentially float in the surrounding ice, and thus in Hallet's model abrasion scales with the clast velocity, its buoyant weight, and the bed-normal force exerted on the clast by ice flowing around it.

EROSION LAWS AND LAND-FORM DEVELOPMENT

McGee realized that he could not use his equations to compute absolute rates of erosion because they contained a variety of parameters of unknown magnitude and spatial variability, designed to represent real-world complications to his ideal models (McGee, 1894, p. 354). However, by assuming the unknowns were either constant or varied in some predictable fashion, for situations in which spatial variations in flow velocity and ice weight were known or could be predicted, McGee could estimate erosion patterns from each erosion law. Thus, by assessing which erosion law yielded erosion patterns most likely to produce land-form evolution toward observed forms, McGee could judge which erosion law was most likely to be dominant in any given situation. This was perhaps a rather circular methodology, but it did allow McGee to generate considerable insight into the basic boundary conditions necessary for the development of a number of characteristic glacial land forms that were poorly understood at the time.

The development of U-shaped valleys

Although the term U-shaped valley was credited by Charlesworth (1957) to Helland (1877),* it was probably first used in a rather obscure book by J.F. Campbell in 1865. Campbell constructed a geological alphabet to help travellers interpret the "language" of land forms, and used the term U-shaped to describe the cross-sectional forms of river canyons and glaciated valleys. It was only in the work of McGee (1883, 1894) that the term became synonymous with glaciated valleys, although it may well have been suggested to McGee by LeConte's (1873) work in the Sierras which included a graphic comparison of V-shaped unglaciated valleys with (U-shaped) glaciated troughs (Fig. 2), although LeConte did not use the term U-shaped in his work.

Fig. 2. A comparison of unglaciated, V-shaped valleys and glaciated troughs (from LeConte, 1873, p. 341). As McGee worked briefly in the Sierras early in his career, it is likely that he was familiar with LeConte's work, and this diagram may have prompted him to use the term U-shaped for glaciated valleys. (Reproduced by permission of the American Journal of Science.*)*

McGee viewed the U-shaped cross-section as one of the most characteristic features of glacial valleys, and considered it likely to have been developed as a result of glacial erosion acting on an originally V-shaped riverine valley. From simple geometry, it was clear to McGee that to convert a V-shape to a U-shape required perferential removal of material from the channel wall, regardless of the amount of overall channel widening or deepening that might also be involved. Thus, the erosion pattern under a glacier had to include a maximum away from the centre of the channel. Clearly, if erosion was maximum at the centre of the glacial channel, the initial V-shape would simply be deepened, developing broadly convex-inwards rather than

* Curiously, Helland's (1877) paper in fact contains no mention of U-shaped valleys.

https://doi.org/10.3189/S0022143000009357 Published online by Cambridge University Press

concave-inwards channel walls. With a specific erosion pattern in mind, McGee attempted to determine which of his erosion laws would be most likely to produce the desired pattern.

To apply his erosion laws to the evolution of valley cross-sections required that McGee determine the distribution of ice velocity (v) and weight (w) across a V-shaped valley occupied by ice. McGee calculated the effective pressure at the bed of a glacier from the depth of overlying ice, thus for a V-shaped cross-section, w increased linearly from the margin to the centre of the channel. From observations on the surface of glaciers by Forbes (1859) and Tyndall (1860), McGee was aware that surface velocity was generally maximum at the centre of straight sections of glaciers, and declined rapidly close to the margins. With both w and v increasing towards the centre of the glacier, and as I and F involve the product of w and v (Equations (1) and (3)), only by appealing to spatial variations in the unknown factors could the erosion laws represented by Equations (1) and (3) produce an erosion maximum away from the centre of the glacial channel. However, McGee's measure of erosion effectiveness could easily produce the desired channel-wall erosion maximum:

> "Since glacier ice but slightly approaches perfect fluidity and the flow of the center is greatly retarded by the sides, the ratio of impulse to weight (and with it the effectiveness) continually and largely increases from center to sides: if the central effectiveness be just zero, that at the sides will nevertheless remain important; if it be minus centrally, it may still be considerable laterally; and however great may be its value at the center, it must have far greater values at the sides. The disposition, then, will ever be to protect the bottom and equally to attack the sides of the valley; and since the down-stream impulse ... forms a curve ... so will the disposition also be to form concave valley-sides" (McGee, 1894, p. 358).

What is not clear from this explanation is whether McGee envisaged erosion to be maximum right at the margin of the glacier, or if the maximum was somewhere between the centre and the margin (a mid valley-wall position). Without adding further complications to the theory, only the latter situation could produce the desired U-shaped form. If erosion increased continuously from the centre to the margin, the resultant form would be convex-inwards rather than concave-inwards (U-shaped).

In his explanation of the U-shaped valley, McGee clearly favoured the idea that erosion at the centre of the channel is negligible, in part because this allowed him to explain two additional observations: first, McGee was struck by the presence of loose debris in the middle of formerly glaciated valleys, and apparently had difficulty reconciling this with the idea of intense glacial erosion. However, an erosion pattern with a minimum at the centre of the channel would allow zero erosion or even deposition in the middle of the channel at the same time as erosion was taking place on the channel walls to produce a U-shaped cross-section (see also Boulton, 1974). It does not seem to have occurred to McGee to explain the loose material at the centre of the valley as material deposited during glacier retreat; secondly, McGee noted that the volume of material in moraines was typically far less than the volume of the glaciated valleys from which the material was derived. If glaciers could not easily erode vertically, then, as most glacial valleys were fairly deep, much of the excavation of the valley had to have occurred prior to glaciation. This meant that the volume of material in moraines only had to match the difference in volume between the original pre-glacial V-shape and the subsequent U-shaped valley, rather than the entire volume of the U-shaped valley (as would have been required by Tyndall's (1862) hypothesis that glaciated valleys were entirely carved out by glacial erosion). This implicit minimum estimate of the amount of glacial erosion involved in the development of U-shaped valleys is illustrated in Figure 3, in which McGee showed glacial valley development involving valley widening but no deepening.

Hanging valleys

By the 1880s, spectacular waterfalls at sites Gilbert would later term *hanging valleys* (Davis, 1900, p. 288) had been noted in the Alps and Norway (e.g. Forbes, 1853), but typical explanations of this frequent discordance in elevation between tributaries and main valleys in alpine areas were couched in terms of recent river rejuvenation as a result of regional uplift. During the hypothesized uplift period, the main rivers, with greater discharge and thus erosive ability, could cut down more quickly than their tributaries, leaving the tributaries progressively "hung up" above the main rivers (see Davis' (1900) review of the work of Reuss and Heim in the 1860s and 1870s).

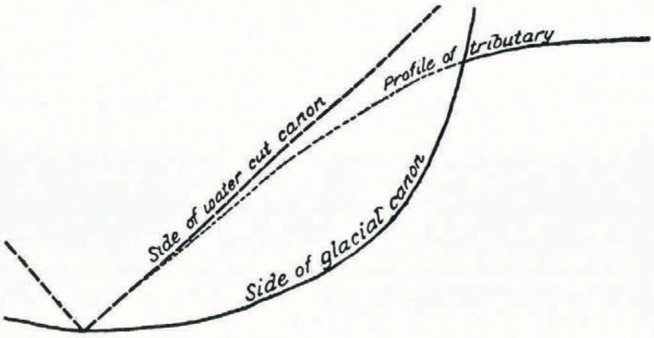

Fig. 3. The development of a U-shaped cross-section from an originally V-shaped valley, illustrating the origin of hanging tributary valleys (McGee, 1894, p. 360). The area between the tributary profile and the glacial canyon represents the volume of material eroded by glacial action.

Although Davis (1900) credited McGee (1883) with the first explicit glacial explanation for hanging valleys, McGee's work came several years after Hellands's (1877) clear analysis of the problem:

> "If a glacier fills a tributary valley, and is thinner than that in the main valley, the depth to which it erodes its bed must be less than the depth of the main valley. Hence many tributary valleys must debouch high above the bottom of the main valley. Instances abound of tributary valleys debouching thousands of feet above the beds of main valleys, along the steep sides of the fjords of Western Norway" (Helland, 1877, p. 174).

While Helland's explanation emphasizes differential rates of *vertical* incision, and this implies substantial glacial erosion, in McGee's explanation *lateral* erosion in the main valley effectively undercuts the long-profile of the tributary (Fig. 3):

> "If now the main cañon become filled with ice and be transformed from the V to the U type by its action, the distal extremity of the tributary will be cut off and the original stream-formed declivity replaced by the precipitous side-wall of the normal glacier valley ... " (McGee, 1894, p. 359).

Interestingly, McGee's explanation involved a rather surprising convex long-profile for the tributary valley (Fig. 3), which he argued resulted from rapid down-cutting of the main valley in pre-glacial times:

> "In a region of rapid corrasion then, the main stream must ... more rapidly corrade its channel than does its minor tributary; and the tributary cañon must accordingly enter its principal over a rapid or at least a convex curve in longitudinal profile" (McGee, 1894, p. 359).

This appeal to the special case of rapid pre-glacial river down-cutting, perhaps reflecting the influence of Heim's fluvial explanation for hanging valleys, allowed McGee to postulate negligible deepening of the valley by glacial erosion, and thus derive an absolute minimum estimate for the amount of glacial erosion involved in excavating a U-shaped valley (Fig. 3). With a convex tributary profile, simply by *widening* the main channel an impressive hanging tributary would be formed. In contrast, Gilbert (1903), who favoured more marked glacial erosion, used a concave

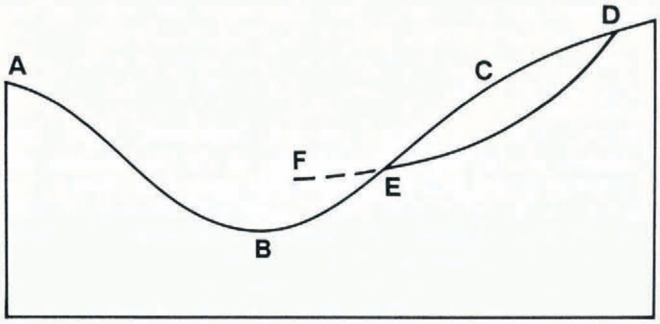

Fig. 4. A method to estimate the amount of glacial deepening in an alpine valley based on the extrapolation of tributary-valley long-profiles (redrawn from Gilbert, 1903, p. 116). Note the graded, concave long-profile of the tributary valley, in contrast to the convex profile in Figure 2. "ABC in the diagram is the cross-profile of a main glacial trough, DE the longitudinal profile of a tributary trough, and EF the produced floor of the tributary ... FB is the measure either of the deepening of the main trough by the glacier, or of the difference between that deepening and the deepening of the tributary" (Gilbert, 1903, p. 116-17).

(graded) long-profile for the tributary valley, allowing him to argue that hanging valleys indicated considerable *deepening* of the main valley (Fig. 4). This latter aproach, involving reconstructing pre-glacial valleys assuming initially graded junctions, was favoured by Davis (1900) and Matthes (1930), and produced results that, perhaps more than any other line of evidence, provided confirmation of the significance of glacial erosion to geologists in the early twentieth century.

Long-profile overdeepenings

McGee observed that glaciated valley long-profiles often consisted of a series of large steps, which in some cases were overdeepened. These overdeepened basins, now often occupied by large lakes, had been attributed to glacial erosion by Ramsay (1859, 1862a), although Lyell (1865), Murchison (1864), and Judd (1876) maintained they were of tectonic origin and were sceptical of any explanation of rock basins in terms of glacial erosion.

Ramsay's most detailed attempt to explain how glaciers actually formed rock basins involved a suggestion that glacial erosion was generally proportional to ice thickness and, rather strangely (see Moore, 1865), *inversely* proportional to the basal gradient (Ramsay, 1865). With this characterization of the controls on erosion, Ramsay suggested that maximum erosion should occur where a valley glacier emerged on to an adjacent plain (low basal gradient and large ice thickness) and this, he argued, explained the frequent occurrence of large lake basins at the margins of alpine areas. As Moore (1865) was quick to point out, Ramsay's explanation involved a somewhat unsatifactory description of the relationship between basal gradients and erosion, and was not really able to explain overdeepenings in locations other than at the margins of alpine areas.

In an attempt to provide a more general explanation of the development of steps and overdeepened basins, McGee used his erosion laws to predict the pattern of erosion associated with initial (pre-glacial) irregularities in the long-profile of a glacial valley. Assuming that the surface slope of the glacier was approximately uniform, McGee argued that where there were minor depressions in the bed, greater ice thickness (w) and slightly reduced velocities (v) would give locally higher values of intensity and friction (Equations (1) and (3)), but lower values of effectiveness (Equation (4)). Greater intensity and friction would tend to encourage development of these initial small depressions into major overdeepenings:

"If now an otherwise uniform V cañon of irregular gradient become occupied by a glacier, the flow, varying as it does with the declivity, will become unequal and ice will tend to accumulate on the planes of low declivity until it approaches a uniform surface slope; when the weight of ice at different points ... of the glacier will become variable, and will reach a maximum over the greatest depression.
[Although] it cannot be determined in the ordinary case whether the disposition will be to erode more rapidly where weight increases at the expense of declivity, or where the reverse occurs; ... it appears quite certain that where the surface declivity materially exceeds that at the base, and where, accordingly, the impulse is not reduced proportionally to the declivity of the channel, erosion must progressively increase with the weight. If so, the tendency of glaciers must be to cumulatively intensify the irregularities in gradient normal to water-cut cañons" (McGee 1894, p. 360-61).

However, McGee also recognized that eventually a negative feed-back would set in when the reverse gradient at the down-glacier end of the overdeepening significantly reduced ice velocities and allowed ponding of water beneath the ice. Consequently, he argued that there was a limit to the relative depth of the overdeepening that could develop:

"... whenever the depression becomes so considerable as to possess reverse slope towards its distal extremity, gravity will no longer enhance, but instead oppose, direct transportation of detritus ... . In a like manner, when the normal slope becomes reversed, gravity will oppose and not enhance transportation by subglacial water ... . [F]inally, when the depth of the depression below its distal rim reaches 0.92 of the maximum depth of the ice, the ... incumbent ice will suffer flotation, and both corrasion and transportation will practically cease. Thus, the excavation of depressions by direct ice-action has a definite, though indeterminate limit, and can probably never exceed a moderate fraction of the depth of the ice" (McGee, 1894, p. 362).

Finally, McGee recognized that basal ice may stagnate in an overdeepening (see also Nye and Martin, 1968):

"... the longitudinal perimeter of the depression must continually increase until the friction along it approaches and ultimately equals the shearing strength of the ice along its chord, whence the movement of the basal segment must concurrently diminish and gradually cease" (McGee, 1894, p. 362).

Although McGee ascribed overdeepenings to glacial excavation, he still managed to maintain his view that the total amount of glacial erosion that had occurred in many alpine areas was relatively small. He argued that in a typical alpine area glaciated rock basins were relatively rare, and rock steps were not much more frequent than in areas that had not been glaciated. Thus, the main features of glacial valleys were all ascribed to a relatively small modification of pre-existing fluvial topography.

SUMMARY AND CONCLUSIONS

W.J. McGee was a scientist of varied interests who, in a brief excursion into theoretical glacial geomorphology, provided an unprecedented analysis of glacial erosion laws and the development of glacial land forms. He provided the first detailed, process-oriented explanations for U-shaped valley cross-sections and long-profile overdeepenings, and one of the first explicitly glacial explanations for hanging valleys. In many ways, his work was unequalled in glacial geomorphology until Boulton's (1974) development of a model for glacial abrasion and its application to the evolution of glacial land forms. In retrospect, McGee's work may appear somewhat skewed by his belief in relatively minimal glacial erosion, but this was not an unusual view at the time. Even A.C. Ramsay (1862b), the most ardent nineteenth century advocate of a glacial origin for alpine lake basins, argued that glaciers do not significantly deepen their valleys except in very specific locations, and it was not until early in the twentieth century that the possibility of significant vertical erosion by glaciers became widely accepted.

In some respects, the fate of McGee's work parallels

https://doi.org/10.3189/S0022143000009357 Published online by Cambridge University Press

that of his contemporary and colleague G.K. Gilbert, now considered by many to have been the founder of "modern" process-oriented approaches to geomorphology. Gilbert's emphasis on understanding processes in the landscape and the regulatory effects of what would now be termed negative feed-back was overshadowed by Davis' evolutionary approach to understanding land-form and landscape development — in part because Davis' work was more in tune with the essentially Darwinian ethic of the time. The recent surge of interest in Gilbert's work (e.g. Baker and Pyne, 1978; Chorley and Beckinsale, 1980) can be explained largely in terms of changes in the ruling paradigm in geomorphology, and illustrates how past work is re-evaluated in the context of an evolving discipline. In recent years, explanations of the evolution of glacial land forms and landscapes have increasingly involved combining glacial erosion laws with a knowledge of ice dynamics (e.g. Nye and Martin, 1968; Röthlisberger, 1968; Johnson, 1970; Boulton, 1974; Sugden, 1978; Oerlemans, 1984; Harbor and others, 1988) and thus, largely unwittingly, the approach to glacial land-form explanation pioneered by W.J. McGee is being revived.

ACKNOWLEDGEMENTS

My initial interest in glacial land forms was fostered by Dr J.M. Grove's scholarly guidance and friendship during my undergraduate studies at Girton College, Cambridge, and I dedicate this paper to her. More recently, I have been able to resume my studies of glacial land forms under the guidance of B. Hallet, with support from U.S. National Science Foundation grant EAR-8708400 and a Shell Companies Foundation fellowship. J. Bourgeois and R. Anderson must share responsibility for reviving my interest in the history of glacial geomorphology and I thank them, as well as J. Walder, S. Porter, J. Warburton, and an anonymous reviewer for their helpful comments on this work.

REFERENCES

Alley, R.B., D.D. Blankenship, C.R. Bentley, and S.T. Rooney. 1986. Till-balance modeling of ice-sheet flow. *Eos*, **67**(44), 949.

Alley, R.B., D.D. Blankenship, C.R. Bentley, and S.T. Rooney. 1987. Till beneath Ice Stream B. 3. Till deformation: evidence and implications. *J. Geophys. Res.*, **92**(B9), 8921-8929.

Anon. 1883. Report on a discussion of Glacial canons by W.J. McGee. *Science*, 2, 315-316.

Baker, V.R. and S. Pyne. 1978. G.K. Gilbert and modern geomorphology. *Am. J. Sci.*, **278**, 97-123.

Bonney, T.G. 1871. On the formation of cirques and their bearing upon theories attributing the excavation of alpine valleys mainly to the action of glaciers. *Q. J. Geol. Soc. London*, **27**, 312-324.

Bonney, T.G. 1874. Notes on the Upper Engadine and the Italian valleys of Monte Rosa, and their relation to the glacier erosion theory of lake basins. *Q. J. Geol. Soc. London*, **30**, 479-489.

Bonney, T.G. 1910. Presidential address to the British Association for the Advancement of Science. *Science*, **32**, 321-336; 353-363.

Boulton, G.S. 1974. Processes and patterns of glacial erosion. *In* Coates, D.R., *ed. Glacial geomorphology.* Binghamton, N.Y., State University of New York, 41-87.

Boulton, G.S. 1986. A paradigm shift in glaciology? *Nature*, **322**(6074), 18.

Boulton, G.S. and R.C. Hindmarsh. 1987. Sediment deformation beneath glaciers: rheology and geological consequences. *J. Geophys. Res.*, **92**(B9), 9059-9082.

Campbell, J.F. 1865. *Frost and fire.* Edinburgh, Edmonston and Douglas.

Chamberlin, T.C. 1888. The rock-scoring of the great ice invasions. *U.S. Geol. Surv. Annu. Rep.* 7, 1885–1886, 147-248.

Chamberlin, T.C. 1895. The classification of American glacial deposits. *J. Geol.*, **3**, 270-277.

Charlesworth, J.K. 1957. *The Quaternary era with special reference to its glaciation.* London, Edward Arnold.

Chorley, R.J. and R.P. Beckinsale. 1980. G.K. Gilbert's geomorphology. *Geol. Soc. Am. Spec. Pap.* 183, 129-142.

Chorley, R.J., A.J. Dunn, and R.P. Beckinsale. 1964. *The history of the study of landforms or the development of geomorphology. Vol. 1.* London, Methuen, John Wiley.

Darton, N.H. 1916. *The McGee Memorial Meeting of the Washington Academy of Sciences ... December 5, 1913.* Baltimore, Williams and Wilkins, 51–60.

Davies, G.L. 1969. *The Earth in decay: a history of British geomorphology 1578–1878.* New York, etc., Elsevier.

Davis, W.M. 1884. Geographic classification illustrated by a study of plains, plateaus and their derivatives. *Proc. Am. Assoc. Advancement Sci.*, **33**, 428-432.

Davis, W.M. 1900. Glacial erosion in France, Switzerland and Norway. *Proc. Boston Soc. Nat. Hist.*, **29**, 273-322.

Davis, W.M. 1909. *Geographical essays.* Boston, Ginn.

Forbes, J.D. 1843. *Travels through the Alps of Savoy.* Edinburgh, A. & C. Black.

Forbes, J.D. 1853. *Norway and its glaciers visited in 1851.* Edinburgh, A. & C. Black.

Forbes, J.D. 1859. *Occasional papers on the theory of glaciers.* Edinburgh, Simpkin.

Garwood, E.J. 1910. Features of alpine scenery due to glacial protection. *Geogr. J.*, **36**(3), 310-339.

Geikie, J. 1895. The classification of European glacial deposits. *J. Geol.*, **3**, 241-269.

Gilbert, G.K. 1903. *Glaciers.* New York, Doubleday, Page and Co. (Harriman Expedition Series, Vol. 3.)

Hallam, A. 1983. *Great geological controversies.* Oxford, Oxford University Press.

Hallet, B. 1979. A theoretical model of glacial abrasion. *J. Glaciol.*, **23**(89), 39-50.

Harbor, J.M., B. Hallet, and C. Raymond. 1988. A numerical model of landform development by glacial erosion. *Nature*, **333**(6171), 347-349.

Harker, A. 1899. Glaciated valleys in the Cuillins, Skye. *Geol. Mag.*, **6**, 196-199.

Helland, A. 1877. On the ice-fjords of north Greenland, and on the formation of fjords, lakes and cirques in Norway and Greenland. *Q. J. Geol. Soc. London*, **33**, 142-176.

Irving, R.A. 1883. On the mechanics of glaciers with especial reference to their supposed power of excavation. *Q. J. Geol. Soc. London*, **39**, 62-81.

Johnson, A. 1970. *Physical processes in geology.* San Francisco, A. Freeman, Cooper and Co.

Judd, J.W. 1876. On the origin of Lake Balton in Hungary. *Geol Mag.*, Ser. 2, **3**, 5-15.

Knowlton, F.H. 1916. *The McGee Memorial Meeting of the Washington Academy of Sciences ... December 5, 1913.* Baltimore, Williams and Wilkins, 76-82.

LeConte, J. 1873. On some of the ancient glaciers of the Sierras. *Am. J. Sci.*, **105**, 325-342.

Lyell, C. 1865. *Elements of geology. Sixth edition.* London, John Murray.

McGee, E.R. 1915. *Life of W.J. McGee.* Farley, IA, private printer.

McGee, W.J. 1883. Glacial canons. *Science*, **2**, 315-316.

McGee, W.J. 1894. Glacial canons. *J. Geol.*, **2**, 350-364.

Matthes, F.E. 1930. Geologic history of the Yosemite valley. *U.S. Geol. Surv. Prof. Pap.* 160.

Moore, J.G. 1865. On lake basins. *Philos. Mag.*, **29**, 526-527.

Murchison, R.T., *Sir.* 1864. Glaciers of the Himalaya mountains and New Zealand compared with those of Europe. — On the powers of glaciers in modifying the surface of the Earth, and on the agency of floating icebergs. *J.R. Geogr. Soc.*, **34**, clx-clxxx.

Nye, J.F. and P.C.S. Martin. 1968. Glacial erosion. *International Association of Scientific Hydrology Publication* 79 (*General Assembly of Bern 1967 — Snow and Ice*), 78-86.

Oerlemans, J. 1984. Numerical experiments on large-scale glacial erosion. *Z. Gletcherkd. Glazialgeol.*, **20**, 107-126.

Ramsay, A.C. 1859. The old glaciers of Switzerland and north Wales. *In* Ball, J., *ed. Peaks, passes and glaciers. Fourth edition.* London, Longman, 400-474.

Ramsay, A.C. 1862a. On the glacial origin of certain lakes

https://doi.org/10.3189/S0022143000009357 Published online by Cambridge University Press

in Switzerland, the Black Forest, Great Britain, Sweden, North America, and elsewhere. *Q. J. Geol. Soc. London*, **18**, 185-204.

Ramsay, A.C. 1862b. The excavation of the valleys of the Alps. *Philos. Mag.*, **24**, 377-380.

Ramsay, A.C. 1864. On the erosion of valleys and lakes. *Philos. Mag.*, **28**, 293-311.

Ramsay, A.C. 1865. Sir Charles Lyell and the glacial theory of lake basins. *Philos. Mag.*, **29**, 285-298.

Ramsay, A.C. 1876. The origin of lake basins. *Geol. Mag.*, **3**, 136-138.

Robin, G. de Q. 1986. A soft bed is not the whole answer. *Nature*, **323**(6088), 490-491.

Röthlisberger, H. 1968. Erosive processes which are likely to accentuate or reduce the bottom relief of valley glaciers. *International Association of Scientific Hydrology Publication* 79 (*General Assembly of Bern 1967 — Snow and Ice*), 87-97.

Sugden, D.E. 1978. Glacial erosion by the Laurentide ice sheet. *J. Glaciol.*, **20**(83), 367-391.

Tyndall, J. 1860. *The glaciers of the Alps*. London, John Murray.

Tyndall, J. 1862. On the conformation of the Alps. *Philos. Mag.*, **24**, 169-173.

Tyndall, J. 1864. On the conformation of the Alps. *Philos. Mag.*, **28**, 225-271.

Tyndall, J. 1872. *The forms of water in clouds and rivers, ice and glaciers*. London, H.S. King and Co.

Washington Academy of Sciences. 1916. *The McGee Memorial Meeting of the Washington Academy of Sciences ... December 5, 1913*. Baltimore, Williams and Wilkins.

MS. received 23 November 1988 and in revised form 4 April 1989