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Eliot Blackwelder and the alpine glaciations of the Sierra Nevada

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INTRODUCTION

Eliot Blackwelder read "Pleistocene glaciation in the Sierra Nevada and Basin Ranges" before the Geological Society of America on December 27, 1929. The article was published two years later (Blackwelder, 1931), 68 years after the Whitney Survey in 1863 discovered evidence of Pleistocene alpine glaciation in the Sierra Nevada of California (Whitney, 1865; Brewer, 1966). J. D. Whitney and his colleagues were inspired by Louis Agassiz, who had earlier inferred the existence of vast, long-vanished glaciers in Europe and beyond. The naturalist John Muir (1872) soon thereafter found active cirque glaciers in the Sierra Nevada, for example on Merced Peak. Muir argued eloquently that vanished glaciers had played a dominant role in sculpting the stunning topography of broad valleys and steep cliffs of the Sierra Nevada, as exemplified by the canyons of the Merced and Tuolumne Rivers. Later, François Matthes (1930) argued that most of the erosion was actually fluvial, and the glaciers only modified the landscape.

By the turn of the century, the existence of large Pleistocene glaciers was widely accepted, and attention was directed toward filling in the details of their fluctuations. How many times did they advance? How long were the glacial periods, and what was the interval between them? How did the glacial history of the Sierra Nevada accord with the presumably better-understood history of the Laurentide ice sheets? These were the questions that motivated Eliot Blackwelder. The summary of his experience and observations in attempting to answer them formed the core of his 1929 address to the society. He began his research into alpine glaciations immediately after receiving his undergraduate degree, working with R. D. Salisbury in the mountains of Wyoming (Blackwelder and Salisbury, 1903), and by 1929 he had nearly three decades of experience.

"Pleistocene glaciation in the Sierra Nevada and Basin Ranges" was a remarkable paper, one that set the tone and topics for most subsequent investigations of alpine glaciations in the American West. It occupies the present midpoint of the history of Sierran glacial studies and is a true "classic," if a classic paper is one that has survived, largely intact, the test of time and has been the nucleus for a de facto school of geological inquiry.

Although Blackwelder (1931) galvanized much subsequent research, and even though his research has a modern feel to it, Blackwelder was very much a product of his times. Most obviously, he worked when access was more difficult than it is today. His geographic coverage is remarkable when viewed from that perspective, but some observations that have proven important were missing. As Blackwelder (1931, p. 866) predicted, even in the eastern Sierra Nevada, which was his geographic focus, he had "mapped only a few of [the glaciated drainages] in the detail their interest merits. It will take many years to complete the mapping, and that work will necessarily be completed by others." Blackwelder studied the effects of the great Pleistocene climatic oscillations, before the marine and ice-core records showing sea-level and climatic fluctuations were measured and analyzed. Blackwelder wrote before the great discoveries in geochronology —radiocarbon, potassium-argon, and cosmogenic-nuclide analysis—that allowed numerical dating of some of the deposits he studied. Working as he did against these handicaps, Blackwelder's insights are all the more impressive.

Blackwelder's writing provides an interesting footnote. At its best it was evocative, almost lyrical; Blackwelder's concern was evidently to convey a powerful impression of the generalized observations he had made. He wrote well. Modern scientific writers might view his style as needlessly wordy; today's science is presented in a more terse, matter-of-fact style. We might also criticize Blackwelder as being occasionally imprecise, or as overgeneralizing. Viewed against his predecessors and contemporaries, however, Blackwelder was notable for his "clear, direct thinking and for expressing complex ideas in simple words" (Krauskopf, 1976).

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In this article we first briefly set the stage for Blackwelder's 1929 speech by reviewing the work of his colleagues in the Sierra Nevada, and recapitulate the main points of his talk and article. We then examine the influence this has had on his intellectual heirs and comment on the changes that have occurred in his field since his talk.

SCIENTIFIC SETTING

Blackwelder focused his studies on the eastern escarpment of the Sierra Nevada and the ranges to the east, sharing the scientific stage with Israel Russell (1885, 1889, 1898), G. K. Gilbert (1890), and Adolf Knopf (1918). Much of the pioneering research on Sierran glaciation had been conducted on the less-arid west side of the Sierra Nevada, and there the work of Clarence King (1878), Henry Turner (1900), and François Matthes (1930) was paramount. In the ranges of the Great Basin to the east, King (1878) and Russell (1885) had reported evidence of former glaciation.

Blackwelder (1931, p. 867) noted that Willard D. Johnson, working with Israel Russell near Mono Lake, was the first to recognize evidence of multiple glacial stages in the Sierra Nevada. Johnson, however, left his findings unpublished, and credit for first publishing on distinct glacial stages in the Sierra Nevada went to Turner and Ransome (1898), although Gilbert (1890) had earlier inferred at least two distinct glaciations throughout the Cordillera. Russell (1889) had recognized multiple advances, but had not claimed that these necessarily represented different stages. To Blackwelder, this was an important distinction: deposits from different stages differed enough to be mapped and correlated regionally, and stages were first-order climatic events, possibly global in scope. Curiously, as we shall see, modern dating techniques may now have blurred some of the boundaries between what had been, to Blackwelder, obviously different glaciations. Nevertheless, in 1931 Blackwelder probably felt he was on solid scientific ground.

Blackwelder (1931, p. 866) focused on the "dry eastern slope of the Sierra Nevada, where the glacial features are best displayed free from obscuring forests" (Fig. 1), but his interest in regional correlation of glacial deposits led him also to consider evidence from the Central Plains, the Rocky Mountains, and the Great Basin, and especially from the western slopes of the Sierra Nevada. Blackwelder carefully examined evidence of past glaciations in the west-slope valleys of the Merced, Stanislaus, American, and Yuba Rivers. Here he crossed paths with Matthes, who was aggressively pursuing similar lines of research, especially in Yosemite Valley (Matthes, 1929, 1930). There Blackwelder and Matthes met to sort out their differences in the field, in September, 1930, while Blackwelder was preparing his manuscript. As Blackwelder (1931, p. 907) wrote: "At that time certain correlations and interpretations were agreed upon. These were later supplemented by a re-examination by the writer in March, 1931." Blackwelder's article was submitted to the Geological Society of America *Bulletin* six weeks later; it must have benefited from Matthes' input. However, Blackwelder's (1931, p. 907) correlations and interpretations were "accepted only in part by Mr. Matthes."

Blackwelder regarded the Central Plains as providing the "standard section" against which the less-developed Cordilleran evidence would be compared and interpreted. Antevs (1925) had suggested that five glacial stages, corresponding to the then-recognized five stages of the Laurentide ice sheet, would ultimately be recognized in the Cordillera, and Blackwelder felt he was well on the way to realizing Antevs' prediction. Blackwelder (1931, p. 869) assumed that the advance and retreat of the Laurentide ice sheet was driven by "general changes of climate of worldwide influence," and he never questioned that fluctuations in different localities were probably synchronous. Thus, he displayed a predilection for incorporating field observations and interpretations into a neat, theoretical package, in this case supplied by his presumptions on how the global climate system actually behaved. This explains his concern with correlation: the existence of global climatic fluctuations gave correlation exercises a strong rationale, because glaciations really were synchronous. As Blackwelder (1931, p. 919) put it:

> *PURPOSE OF THE CORRELATIONS*
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> The writer is interested in the glacial stages of the West, not so much for their own sakes as for their utility in reconstructing the Pleistocene history of the Cordilleran region. Many individual events in that history have been determined, but serious difficulties are encountered when the attempt is made to arrange these in consecutive historical order and still more when one tries to fit such a sequence into the general scheme of the period. Fossils are rare, and even when found they give but little comfort, because the evolutionary changes among organisms were too slow to bring about very distinct faunas within the Pleistocene period–especially in the later part.
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> The best and most convenient criteria at present available for working out the sequence of Pleistocene events are physiographic. For general correlations there seems to be no basis as good as that afforded by the climatic pulsations for which the Pleistocene period is noted. Such climatic variations, if due to general atmospheric or perhaps astronomic causes, must have affected all parts of the region and impressed their record upon its topographic forms and deposits. Basins held fresh lakes during the cooler epochs, but only playas or salinas in the intervening dry times. Alluvial fans grew larger in the more arid ages and were intrenched under the influence of the next cool moister régime. Such illustrations serve to indicate how the establishment of a series of climatic ages may facilitate the integration of a continuous history of the Pleistocene period in western United States.
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> Already tentative correlations have been extended out from the glacial area of the Sierra Nevada to the desert basins eastward as far as Death Valley and thence to the Colorado River. The great pediments and alluvial fans as well as the lake terraces and salt beds can thus be assigned to approximate geologic dates and still older features referred to them in turn.

Figure 1. "Moraines along the east base of the Sierra Nevada southwest of Mono Lake. In the center of the view a large smooth lateral moraine of the Tahoe stage extends out from Bloody Canyon. The scarcity of boulders and the absence of a terminal moraine are typical. To the right, in front of Mount Dana, is a maturely eroded mass of till of the Sherwin stage resting upon granite; the white lines mark the contact. The Tioga stage moraines of Bloody Canyon are scarcely visible" (Blackwelder, 1931, Plate 23). Bloody Canyon has been studied repeatedly since Blackwelder's visit (Sharp and Birman, 1963; Burke and Birkeland, 1979; Gillespie, 1982; Birkeland and Burke, 1988; Phillips et al., 1990).

It should not be supposed, just because of his seeming preoccupation with distinguishing stages from advances (which might occur several times within a stage), that Blackwelder was naive or entranced by geologic nomenclature. Instead, his was a more pragmatic, modern concern. Commenting that "the difference of opinion is more apparent than real" Blackwelder (1931, p. 869), seemed to regard the issue of the number of glacial stages as of interest in that their recognition enabled correlation across vast regions. Blackwelder employed the terms *age*, *stage*, and *epoch* interchangeably, all to indicate a time in which alpine glaciers advanced to occupy valleys far from their cirques, although he specifically claimed to "use at present the terms *age* and *stage* for the times and deposits of the major individual glacial and interglacial advances and retreats" (Blackwelder, 1931, p. 869).

"PLEISTOCENE GLACIATION IN THE SIERRA NEVADA AND BASIN RANGES"

Blackwelder (1931) divided his article into two main parts: the glaciations of the eastern slopes of the Sierra Nevada, and correlation with the ranges to the east and the Central Plains. In the first section, he focused on three topics: the number of glacial stages, criteria by which deposits and landforms could be assigned relative ages, and the duration of the glacial stages. In addition, Blackwelder discussed the characteristics associated with each of the four glacial stages that he recognized.

In the second section, Blackwelder correlated the Sierran glacial stages with other alpine glacial stages, and with the "standard section" offered by the tills of the Central Plains. Essentially, Blackwelder used two approaches: landforms and till were correlated on the basis of their degree of weathering, and sequences of stages were correlated by their number and relative duration or spacing in the different regions.

"Eastern slope of the Sierra Nevada"

One of Blackwelder's contributions (Blackwelder, 1930) was to add a fourth glacial stage to the three advances noted by Russell (1889). Blackwelder regarded all four as stages and gave them local geographic names, to preclude unnecessary literature revision should anticipated correlations with the "standard section" not hold up. He commented that Matthes (1930) had adopted the name "Wisconsin" for the youngest stage in Yosemite, because the correlation seemed unimpeachable. Yet, Blackwelder conservatively resisted what must have been, for him also, a reasonable thing to do. His four stages were, in order of increasing age, the Tioga, Tahoe, Sherwin, and McGee stages. Blackwelder suspected that, to match the "standard section," a fifth stage would ultimately be detected as well, falling between the Tahoe and Sherwin stages. He correctly predicted that the evidence would be found near Mono Lake, as it was 32 years later (Sharp and Birman, 1963).

Blackwelder expressed dissatisfaction with the application to Cordilleran deposits of relative dating criteria commonly used in the Central Plains. Soil development in the semiarid West was more difficult to decipher, for Blackwelder, than soil development in the more humid East and Midwest. Relevant fossils and loess were notably absent in the Sierra Nevada.

To fill this void, Blackwelder contrived a long list of relative weathering criteria for use in the West. Chief among these were degree of landform erosion (Fig. 2), boulder weathering (Fig. 3), and degree of stream dissection. Stratigraphic relations between till and tephra were also employed, as were geographic sequences

Figure 2. "A granite Roche Moutonnée of the Tahoe Stage. The view, taken in Leavitt Meadow, shows how weathering and erosion have changed its original smooth, rounded contour to one that is more angular and ragged" (Blackwelder, 1931, Fig. 13). Leavitt Meadow is east of Sonora Pass, in California. Blackwelder was evidently misled by the "ragged" appearance of the outcrop, which was buried deep under a Tioga glacier (Clark, 1967) and either never possessed a "smooth, rounded contour," or lost it to postglacial erosion.

Figure 3. "Typical isolated granite boulder on the Sherwin Till, Rock Creek Plateau. The rock is cavernous and crumbly (rule 6 inches long indicates size of boulder)" (Blackwelder, 1931, Fig. 23). Blackwelder pioneered the systematic estimation of boulder weathering for the relative dating and correlation of moraines.

within valleys. Possibly the most widely quoted and distinctive measure was Blackwelder's GWR (granite weathering ratio). This involved counting granodiorite boulders exposed on moraine crests, for example, and classifying them into three categories according to their degree of weathering: "(a) almost unweathered; (b) notably decayed on the surface but still solid; and (c) greatly weathered, cavernous, or rotten" (Blackwelder, 1931, p. 877). Characteristic ratios, which admittedly varied with climate, were associated with deposits of the different stages. Blackwelder recognized the effects of forest fires on the GWR, but somehow thought that the effects of fire-spalling could be differentiated from those of chemical weathering, all over a time he recognized as spanning tens of thousands of years!

Blackwelder discussed more than 20 relative-weathering criteria. Perhaps because of problematic situations posed by spatially variable fire effects, wind exposure, and rock jointing, he cautioned against reliance on any single one. Realistically, not all criteria could be used in each locality, but even a small set of criteria could strengthen the conclusions greatly. Blackwelder seems to have trusted boulder counts and even systematized field observations over subjective judgment of age.

Blackwelder and his contemporaries lacked the necessary tools to come to grips with questions about the duration of glaciations and the intervals between advances of the glaciers. The more quantitative relative-weathering criteria afforded a scheme for assessing duration, but the scheme was necessarily speculative and unreliable. The interval between the Tioga and Tahoe stages, for example, was estimated by Knopf (1918) as five units and by Russell (1925) as two and a half units, where a single unit represented the time since retreat of the Tioga glaciers. To Blackwelder, this would have meant that the Tahoe stage was as old as 125 ka, if the Tioga deglaciation was taken to have coincided with retreat of the Wisconsin glaciers in the Central Plains, estimated by Antevs (1925) to have begun 25 ka and ended 10 ka years ago. Argued similarly, the Sherwin stage would have been ~50 units (<1.25 Ma) and the McGee stage perhaps 150–250 units (<6 Ma). Blackwelder did not *believe* these age estimates; he thought that they helped clarify the "historical view."

"The Tioga stage." Blackwelder completed his discussion of the eastern Sierra Nevada by giving specifics on locations and characteristics of deposits and glaciated terrain of his four stages. He named the youngest after Tioga Pass, where he regarded Tioga-age landforms and deposits as well displayed. To Blackwelder (1931, p. 882):

> The glacial features that were made by the ice tongues of the Tioga epoch are even now almost as fresh and unaltered as at the time of their formation. The cirques are still as bare and ragged as if recently abandoned by the ice. Talus cones are few and small where the rocks are not closely jointed, and have not grown to large size even where the closer spacing of joints is favorable to frost action. The original polished and striated surface is still rather generally intact, even on such easily weathered rocks as coarse granite. Acres of polished and grooved rock are a familiar sight near Tenaya Lake (Yosemite National Park) and many other places in the high Sierra. If it were not for the destructive effects of forest fires, such surfaces would be even more completely preserved.
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> The lateral moraines generally stand out as bold embankments, marred only by few landslides and by sharp ravines where tributary brooks descend the canyon sides. The terminal moraines are still complete, except for V-shaped notches through which the main streams tumble down to the plains beyond. As the distinctive glacial topography of the moraines is almost entirely preserved, it is generally an easy task to map them continuously.

Tioga moraines were bouldery, and the boulders were largely fresh. Lakes were commonly found behind end moraines.

"The Tahoe stage." Tahoe moraines were characterized by Blackwelder as more eroded than Tioga moraines; axial streams were deeply incised; lakes were filled or marshy; and boulders were less abundant and more heavily weathered. Some boulders were "decidedly rotten" In Mono basin, tephra blanketed Tahoe moraines, but not adjacent Tioga moraines. Although he concluded that the Tioga and Tahoe glaciers belonged to different stages, Blackwelder clearly agonized over this judgment. In the end, he may have been swayed by the appearance of some cirques that he supposed had been occupied by Tahoe, but not Tioga, glaciers; here the contrast between the subdued forms and deep talus of the "Tahoe" cirques contrasted dramatically with the "ragged" Tioga cirques.

"The Sherwin stage." The Sherwin stage was named for the area north of Sherwin Hill, near the town of Bishop. The original topographic expression of Sherwin deposits has long been lost, and main streams have cut deeply into underlying bedrock. Exposed granitic boulders are thoroughly weathered, and even subsurface boulders are grusy. In some valleys, Sherwin-age deposits are in close proximity to younger Tahoe and Tioga moraines from the same drainages, although considerably more extensive. Yet, sufficient time had elapsed since the Sherwin stage that, elsewhere, erosion or "diastrophism" had eliminated the lower-elevation Sherwin deposits, leaving the Tahoe and Tioga moraines unaffected.

"The McGee stage." Evidence of the McGee stage is preserved only in unusual localities, most notably the top of McGee Mountain, 800 m above the modern McGee Creek and its flanking moraines. Original topographic expression was entirely destroyed. Blackwelder expressed concern that McGee "tills" were glacial, and not mudflow deposits.

Extent of glaciers. Blackwelder regarded Tahoe moraines as longer than Tioga moraines of the same drainage, terminating in some cases as much as 500 ft (152 m) lower in elevation. They were also more voluminous, by an estimated factor of 50 in the Bridgeport Basin (Fig. 4). This conclusion was significant, because it drove Blackwelder to regard the Tioga glaciers, even in their cirques, as thinner and less extensive than their Tahoe ancestors, an inference no doubt supported by the subdued nature of some of his "Tahoe" cirques. Blackwelder viewed Tahoe glaciers west of the Sierra crest as confluent, in contrast to the presumably isolated glaciers of Tioga time. Large tracts of bare, heavily weathered granitic bedrock in the Sierran uplands were attributed to Tahoe-stage abrasion, consistent with the supposed small size of the Tioga glaciers.

"Correlations"

"Western slope of the Sierra Nevada." Blackwelder's immediate concern, and most of his emphasis in the article, was correlating his glacial sequence from the eastern Sierra with that of Matthes to the west. The challenge here was that, because the climatic conditions and vegetation differed across the crest of the Sierra, the relative weathering criteria were difficult to apply. Blackwelder considered two drainages, Yosemite and Yuba Valleys. In Yosemite, he concluded that Matthes' Wisconsin stage included both the Tioga and the Tahoe stages; Matthes' El Portal and the Sherwin stages were the same; and evidence for the McGee stage was lacking (Table 1). Blackwelder considered the moraines on the floor of Yosemite Valley near El Capitan to mark the maximum extent of the Tahoe glaciers and relegated the Tioga glaciers to positions far upvalley, for example, above Nevada Falls. Blackwelder's interpretation of Yosemite accorded well with his preconception from the eastern slope that Tioga glaciers were much smaller than Tahoe glaciers, but both were probably in error. Today, the Tioga end moraines, not the Tahoe, are thought to be the ones near El Capitan, and it is possible that remnants of Tahoe moraines were mistakenly identified as El Portal till by Matthes.

For all of his emphasis on the GWR, Blackwelder seems to have relied exclusively on subjective assessments of his relative weathering criteria in drawing his conclusions in Yosemite. However, he did use GWR values and boulder frequencies in correlations with the Yuba Valley glaciations, coming to similar

Figure 4. "Robinson Canyon near Bridgeport [California]. The view shows a frontal moraine of the Tioga stage (XX) only 30 ft high, with a 700-ft lateral moraine of the earlier (Tahoe) stage on the left" (Blackwelder, 1931, Fig. 11). Evidence such as this persuaded Blackwelder that Tioga moraines were commonly much smaller than Tahoe moraines; yet, at this locality the Tioga end moraines could be traced to high lateral moraines deposited against the Tahoe moraines that caught Blackwelder's eye.

Tentative Correlation Table of Glacial Stages in Western United States

Iowa and Illinois	Montana	Wyoming (Wind River)	Colorado (San Juan)	Utah (Wasatch)	Nevada (Ruby Mts.)	Sierra Nevada East	Sierra Nevada Yosemite Matthes
Wisconsin	Wisconsin	Pinedale	Wisconsin	"Younger"	Angel Lake	Tioga	Wisconsin
Iowan	Iowan (?)	Bull Lake	Durango	"Older"	Lamoille	Tahoe	
Illinoisan	....	....	....	....	....	—?—	
Kansan	Kennedy	Buffalo	Cerro	....	—?—	Sherwin	El Portal, Glacier Pt.
Nebraskan	....	....	....	....	....	McGee	

Table 1. "Tentative Correlation Table of Glacial Stages in Western United States"(Blackwelder, 1931, p. 918).

substantive conclusions that Tioga ice descended only to 6500 ft (1980 m), compared to 4000 ft (1220 m) for larger and more vigorous Tahoe glaciers.

Ranges of the Great Basin. Blackwelder's discussion of glaciation in the Basin Ranges was more cursory than for the Sierra Nevada, probably because his reconnaissance there was briefer. Yet the same was true of his correlation with the Rocky Mountains, where he had worked extensively on the Big Horn Range and later in the Tetons and Wind River Mountains (Blackwelder, 1915).

In the Ruby Mountains, Nevada, Blackwelder recognized two glacial stages, which he correlated to his Tioga and Tahoe stages. He claims he did so "by applying there the methods developed on the dry eastern slope of the Sierra Nevada" (Blackwelder, 1931, p. 911), but if this is the case, there is little sign of it in his writing; instead, he resorted to generalizations and evocative prose ("wild crags of the freshly torn cirques") to make his case. Perhaps he collected data but was frustrated in their interpretation, for he reported concerning the Tahoe moraines "the boulders are somewhat more decayed than is usual on moraines of this age, but the value of the comparison is diminished because the rocks... were gneisses of sedimentary origin" (Blackwelder, 1931, p. 911). Regardless, he came to the conclusion that here, as in the Sierra, Tioga glaciers were diminutive, barely reaching down to 8000 ft (2440 m) elevation, in contrast to the massive Tahoe glaciers that crossed the range front. Throughout the remainder of the Great Basin, the story was much the same: Tioga and Tahoe evidence abounded, with hints here and there of older (and therefore Sherwin) tills.

In the Wasatch Range, Utah, Blackwelder was back on more solid ground, partly because Atwood (1909) had independently made the claim for two distinct stages there, and partly because the Sierran relative weathering data—GWRs and boulder frequency counts—seemed to work once more, on the granitic rocks. The story was again the same: an early, bulky Tahoe equivalent, and smaller Tioga equivalents. Blackwelder connected Lake Bonneville shorelines with Tioga-equivalent moraines at Little Cottonwood Creek, demonstrating that the latest glaciation and lake high stand were coeval.

"Rocky Mountains." In the Rocky Mountains of Wyoming, Blackwelder (1931, p. 916–917) was content to observe "an obvious parallelism between the three stages of Wyoming and the Sherwin, Tahoe, and Tioga stages in California," citing in a general way the decay of boulders, the extent and depth of post-glacial stream erosion, and the "relations of moraines to valleys" to support this opinion.

The story in Colorado and Montana was much the same. In the San Juan Mountains, Colorado, Blackwelder (1931, p. 916) found that "the Durango stage is represented by large moraines inside the canyons and by gravel valley-train terraces 150–250 ft above the creeks. This indicates the Tahoe stage. The Wisconsin moraines are lower, lie within the Durango moraines, and are connected with gravel terraces only 20–30 ft high, thus conforming closely to the Tioga stage of the Far West." For Montana, Blackwelder relied on Alden, who recognized three stages (e.g., Alden, 1932), which he related to the three Blackwelder recognized in the Tetons.

Laurentide ice sheet. Blackwelder (1931, p. 917–918) did not feel competent to extrapolate his results to the plains, but relied on W. C. Alden, who had "traced [the glacial formations of the prairie states] more or less continuously from Iowa across Nebraska, South Dakota, and Montana to the Rocky Mountains," for correlation to the "standard section." Evidently, Blackwelder at one point also had a field conference with G. F. Kay, who had studied the Laurentide sequence in Iowa (Kay, 1931). According to Blackwelder, Alden concluded that the Pinedale and Bull Lake stages of Wyoming corresponded to the continental Wisconsin and Iowan stages (Table 1). "Although realizing the liability of error," Blackwelder (1931, p. 918) forwarded his correlations as a "tentative scheme for continuing studies."

In particular, correlations of older tills were uncertain. Nevertheless, "The absence of stages [in the West] equivalent to the Illinoisian stands out... as a challenge" (Blackwelder, 1931, p. 918). Blackwelder claimed some "rather definite evidence" of such a stage in the eastern Sierra Nevada, presumably in Mono basin. He felt stymied by the difficulties in applying relative weathering criteria to the older tills, concluding that drift of the "missing" stage was difficult to distinguish from the older Sherwin till, and that the evident absence of the moraines was because the glaciers were smaller than the later Tahoe glaciers, and thus exposed only locally.

CHANGES IN THE INTERPRETATION OF SIERRAN GLACIAL GEOLOGY SINCE 1931

Number of stages

Blackwelder predicted the discovery of a fifth, pre-Tahoe glacial stage in the Sierra Nevada, which was realized with Sharp and Birman's (1963) analysis of moraines at Bloody Canyon (Fig. 1). Their "Mono Basin" moraines were preserved accidentally, because the path of the longer Tahoe glacier shifted to the north (the Mono Basin moraines are out of view, behind the moraine complex in Fig. 1). The Mono Basin stage was the first of many new, named Pleistocene glaciations. Joseph Birman's dissertation, inspired by Blackwelder and later published in 1964, correlated glaciations across the Sierra crest and also recognized a pre-Tioga, post-Tahoe stage, later named "Tenaya" at Bloody Canyon by Sharp and Birman (1963). Birman (1964) also turned attention to cirques with two Holocene "Neoglaciations" in addition to Matthes' Little Ice Age glacial events. Sharp (1968) reported evidence of a pre-Sherwin till in Rock Creek, and Clark (1967) found evidence for two other tills between Tahoe and Sherwin(?) deposits above the West Walker River. Gillespie (1982) noticed that the "Tahoe" moraine at Bloody Canyon was composite, consisting of a younger crest and inner flank partly burying a distinctly older moraine that was best exposed near the glacier terminus. In addition, two or three pre-Mono Basin moraine remnants were found up-canyon. In the face of this newfound complexity, some glacial advances were notably missing, in particular, the latest-Pleistocene Younger Dryas tills found in Europe (Clark and Gillespie, 1997).

Geochronology

Numerical dating, unknown in 1931, became feasible three decades later. Radiocarbon dating and dendrochronologic techniques have now made possible quantitative age estimates throughout the Holocene and back into the late Pleistocene. Lichenometry has allowed ages to be estimated for otherwise undatable deposits, at least for geographic areas and age ranges for which independent data have made calibration feasible (e.g., Curry, 1968; Scuderi, 1984). K/Ar analysis has permitted the dating of lavas intercalated with glacial deposits (Dalrymple, 1964; Gillespie et al., 1984). Recently, analysis of exotic nuclides produced by bombardment of rocks by cosmic rays has yielded exposure ages under a wide range of circumstances (Bierman, 1994).

The Tioga advances are now firmly correlated to the late Wisconsin glaciation. In Mono basin, Tioga glaciers began advancing before ~30,000 yr B.P., with the maximum extent of the glaciers achieved between 25,000 and 20,000 yr B.P. and retreat to the cirques completed before 13,200 yr B.P. (Clark, 1997, and written comm., 1998; Benson et al., 1998; Bursik and Gillespie, 1993). The Tenaya glaciers may have retreated after ~31,000 yr B.P. (Bursik and Gillespie, 1993).

The Tahoe stage is more difficult to date, largely because of the wide range of deposits assigned to it (for a recent review, see Gillespie and Molnar, 1995). Phillips et al. (1990) used cosmogenic ^{36}Cl to arrive at a minimum age estimate of ~49,000 yr B.P. (recalculated with production rates of Swanson et al., 1993) for the younger "Tahoe" moraine crest at Bloody Canyon, establishing it as mid-Wisconsin in age. The ^{36}Cl ages of boulders from the older "Tahoe" part of that compound moraine were <185,000 yr B.P. In a different drainage, another "Tahoe" or pre-Tahoe moraine has been bracketed at 130,000–460,000 yr B.P. by $^{39}Ar/^{40}Ar$ dates on interbedded lava (Gillespie et al., 1984). Thus, Blackwelder's Tahoe stage appears to include both Wisconsin and pre-Wisconsin advances. His Tioga and the younger of the Tahoe stages (as well as the intermediate Tenaya stage) now appear to be substages of the Wisconsin glaciation, as he had thought all along (Table 1). Perhaps the older till from Blackwelder's Tahoe moraine at Bloody Canyon, or the Mono Basin moraines it must have buried, are evidence of Blackwelder's sought-for "Illinoisian" stage.

The Sherwin glaciation where it is best exposed, in a roadcut on U.S. Highway 395 north of Bishop, California, underlies Bishop Tuff now dated as ~760,000 yr B.P. (Sarna-Wojcicki and Pringle, 1992) and is probably 40–100 k.y. older (Sharp, 1968; Birkeland et al., 1980). The McGee stage has not been dated.

Paleoclimatology and stable isotope analysis

Blackwelder could not have foreseen the estimation of ice-volume and sea-level fluctuations from the $^{18}O/^{16}O$ analysis of foraminifers from sea-floor cores, yet the marine isotope stages, corresponding to periods of high-latitude glaciation and interglaciation, provide the complete global record he sought to use as a reference for his alpine glaciations. The picture is probably far more complex than he or his contemporaries imagined, but his suspicions about astronomical causes now appear to have been well founded. Dated sediment cores from Mono Lake (Benson et al., 1998) and lakes of the Owens River system (e.g., Smith, 1984) provide sedimentological and isotopic evidence that pluvial and glacial events both were temporally correlated in a general way with the marine record. Perhaps most significant, climate change has supplanted Pleistocene history as a focus of study.

Relative weathering criteria

Recent decades have seen significant advances in relative dating. Sharp (1969) gave it a more numerical, "semiquantitative" foundation; Birkeland (1984) and Burke and Birkeland (1979) added soil development, which had frustrated Blackwelder, to the list of successful measures of relative age. Colman and Pierce

(1981) measured distributions of clast weathering-rind thicknesses; Crook (1986) measured acoustic wave speeds through clasts.

Glacier physics

Work on ice flow rules out the possibility of thin Tioga glaciers flowing down the modest slopes where Blackwelder had them, for example, along the Yuba River (60 m thick; Blackwelder, 1931, p. 909). Tioga glaciers, which Blackwelder showed in the East Walker drainage to be 80%–90% of the length of their Tahoe predecessors, were probably proportionately large everywhere else along the eastern slope of the Sierra (e.g., Clark, 1967, Table 3), and to the west. Such large Tioga glaciers would necessarily have nearly the same thicknesses, widths, accumulation areas, and cirques as the Tahoe glaciers at the same places, contrary to Blackwelder's conclusions.

Geomorphology

The equilibrium-line altitude (ELA), not the terminus elevation, is now used as the best measure of climatic conditions (e.g., Porter, 1964). The ELA, which can be reconstructed from the outline and elevations of long-vanished glaciers, is the contact between the zones of ice accumulation and ablation. It is controlled by a gamut of climatic parameters, including temperature and precipitation (e.g., Leonard, 1989). Gillespie (1991) demonstrated that the ELA depression of Tioga and Tahoe glaciers differed by only 10%, and therefore that their surface elevations and widths must have been about the same except near their termini.

In addition, the composite nature of many moraines was recognized at Convict Creek and Bridgeport basin (Sharp, 1969, 1972), Bloody Canyon (Gillespie, 1982), and many other localities. Many Tahoe moraines, for example, were deposited on top of older moraines, whereas the slightly shorter Tioga glaciers did not overtop the Tahoe moraines near their ends, but plastered till on their inside slopes. In the Bridgeport basin, Tioga moraines did locally overtop Tahoe moraines a few kilometers upstream from their ends (e.g., Crook and Gillespie, 1986). This finding cast further doubt on Blackwelder's opinion that the Tahoe moraines were so bulky, and therefore also on some of his correlations.

Major corrections

Blackwelder's conclusion that Tioga glaciers were much smaller than Tahoe glaciers may have been reinforced by the compound nature of Tahoe moraines, with a volume of till deposited over two or more glaciations, but it probably originated from comparing the mass and height of Tioga end moraines to those of nearby Tahoe lateral moraines, and his failure to recognize continuity of Tioga end moraines with many of those big lateral moraines (see Blackwelder, 1931, p. 884). Blackwelder compared small Tioga end moraines to large Tahoe lateral moraines at both Robinson Creek (Fig. 4) and Fallen Leaf Lake (Blackwelder, 1931, p. 889), and at both sites those small Tioga end moraines lead to big Tioga lateral moraines (admittedly easier to see with aerial photographs unavailable to Blackwelder). As a result, Blackwelder (1931, p. 887) mislabeled many Tioga moraines as Tahoe, which in turn led to his incorrect statements that most of the bare granite in the Sierra is Tahoe (rather than Tioga), and that "many [Tahoe] cirques... were not occupied by more recent glaciers."

Blackwelder failed to appreciate the possibility of significant subglacial (or interglacial) fluvial incision of channels into bedrock, and survival of some of those channels under sliding glaciers. This led him to describe the deep bedrock channels on either side of Sonora Pass as remarkable examples of great post-Tahoe fluvial incision (Blackwelder, 1931, p. 893), which erroneously seemed to require the absence of Tioga glaciers at those places. In fact, the channel in granite west of Sonora Pass (near Dardanelles Station) was buried by a Tioga glacier, but might predate it; and channels of Leavitt Creek and the West Walker River, east of Sonora Pass, were both deep under the Tioga glacier (Clark, 1967). Blackwelder's identification of these channels as post-Tahoe required his Tioga glaciers on either side of Sonora Pass to be unrealistically small.

LEGACY

Blackwelder (1931) strongly influenced succeeding Quaternary geologists working in the American West by his emphasis on standardized criteria of relative age, by his determined quest to determine the number of glacial stages and their relative durations, and by his focus on the regional distribution and correlation of glacial features across vast regions. His ultimate goal to describe Pleistocene history may have been supplanted by the effort to understand the processes underlying climatic change, and the ways in which climate can change, but the necessity to know the history of climatic fluctuations is unchanged. For all his relative-weathering criteria, Blackwelder did occasionally fail to distinguish Tioga from Tahoe moraines, and this has led to persistent misconceptions about the relative sizes of the moraines, the extent of the glaciers, and possibly the durations of the glaciations. Regardless of his relatively few serious errors, Blackwelder's work and integration of the research of his colleagues and predecessors inspired the very work that permitted his flaws to be recognized. All of his successors owe him a debt of gratitude for that.

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