Geological Society, London, Special Publications

The Spokane Flood debates: historical background and philosophical perspective

Victor R. Baker

Geological Society, London, Special Publications 2008, v.301;
p33-50.
doi: 10.1144/SP301.3

Notes

The Spokane Flood debates: historical background and philosophical perspective

VICTOR R. BAKER

Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ 85721–0011, USA (e-mail: baker@hwr.arizona.edu)

Abstract: The 1920s–1930s debates over the origin of the 'Channeled Scabland' landscape of eastern Washington, northwestern USA, focused on the cataclysmic flooding hypothesis of J Harlen Bretz. During the summer of 1922, Bretz began leading field parties of advanced University of Chicago students into the region. In his first paper, published in the *Bulletin of the Geological Society of America*, Bretz took special care not to mention cataclysmic origins. However, in a subsequent paper in the *Journal of Geology*, to the editorial board of which he had recently been added, Bretz formally described his hypothesis that an immense late Pleistocene flood, which he named the 'Spokane Flood', had derived from the margins of the nearby Cordilleran Ice Sheet. This cataclysm neatly accounted for numerous interrelated aspects of the Channeled Scabland landscape and nearby regions. Nevertheless, the geological community largely resisted Bretz's hypothesis for decades, despite his enthusiastic and eloquent defence thereof. Resolution of the controversy came gradually, initially through the recognition by J. T. Pardee of a plausible source for the flooding: ice-dammed Pleistocene glacial Lake Missoula in northern Idaho and western Montana. Eventually, by the 1960s, the field evidence for cataclysmic flooding became overwhelming, and physical processes were found to be completely consistent with that evidence. The controversy is of philosophical interest in regard to its documentation of the attitudes of geologists toward hypotheses, which illustrate aspects of geological reasoning that are distinctive in degree from those of other sciences.

J Harlen Bretz (there can be no period after the 'J' – it was the man's entire first name) was born in 1882. He initiated one of the great debates in the history of geomorphology. While not revolutionary in its implications, the debate is, nevertheless, instructive for how it illustrates the workings of science; where the latter is defined not as a sterile collection of facts, or even as a logical application of method, but rather as the collective workings and attitudes of human beings passionately dedicated to the search for truth.

The subject of the debate is an unusual landscape in eastern Washington, northwestern United States, described by Bretz (1928*a*, pp. 88–89) as follows:

> No one with an eye for land forms can cross eastern Washington in daylight without encountering and being impressed by the 'scabland.' Like great scars marring the otherwise fair face to the plateau are these elongated tracts of bare, black rock carved into mazes of buttes and canyons. Everybody on the plateau knows scabland .... The popular name is a metaphor. The scablands are wounds only partially healed – great wounds in the epidermis of soil with which Nature protects the underlying rock .... The region is unique: let the observer take wings of the morning to the uttermost parts of the earth: he will nowhere find its likeness.

The controversy that led to the debate arose because of the interpretation that Bretz made, as he sought to find a single hypothesis that would explain the disparate relationships in this landscape. Bretz (1928*a*, p. 89) argued as follows:

> The volume of the invading waters much exceeds the capacity of the existing streamways. The valleys entered become river channels, they brim over into neighboring ones, and minor divides within the system are crossed in hundreds of places .... The topographic features produced during this episode are wholly river-bottom modifications of the invaded and overswept drainage network of hills and valleys. Hundreds of cataract ledges, of basins and canyons eroded into bed rock, of isolated buttes of the bed rock, of gravel bars piled high above the valley floors, and of island hills of the weaker overlying formations are left at the cessation of this episode .... Everywhere the record is of extraordinary vigorous sub-fluvial action. The physiographic expression of the region is without parallel; it is unique, this channeled scabland of the Columbia Plateau.

Introduction

The unique character of the dry river courses ('coulees') of eastern Washington State was recognized by Reverend Samuel Parker (1838), who provided some of the first scientific observations of the region. He also offered the first, and most prevalent, hypothesis for the origin of the Grand Coulee; he proposed that it was an abandoned former channel of the Columbia River. Lieutenant T. W. Symons subsequently made a government survey of Grand Coulee, describing his travel: 'north through the coulée, its perpendicular walls forming a vista

From: GRAPES, R. H., OLDROYD, D. & GRIGELIS, A. (eds) *History of Geomorphology and Quaternary Geology*. Geological Society, London, Special Publications, **301**, 33–50.
DOI: 10.1144/SP301.3 0305-8719/08/$15.00

like some grand ruined roofless hall, down which we traveled hour after hour' (Symons 1882). In his report, Symons (1882) proposed the hypothesis that the diversion of the Columbia through the Grand Coulee was caused by a glacial blockage of the river immediately downstream of its junction with the coulee. This view was generally accepted for the next few decades (Russell 1893; Dawson 1898; Salisbury 1901; Calkins 1905).

The Grand Coulee was traversed in 1912 by the American Geographical Society's Transcontinental Excursion. This led to several international papers on the coulee authored by participants on the excursion. Henri Baulig, Université de Rennes, described the loess, coulees, rock basins, plunge pools and dry falls ('cataract desechée de la Columbia') for the area (Baulig 1913). He also noted the immense scale of the erosion (Baulig 1913, p. 159): 'peut-être unique du relief terestre, – unique par ses dimensions, sinon par son origine'. Karl Oestreich, University of Utrecht, considered the Grand Coulee to be 'eines machtigen Flusses Bett . . . ohne jede Spur von Zerfall der frischen Form' (Oestreich 1915). He provided another excellent set of descriptions, including features that he recognized to require a special explanation, including granite hills exhumed from burial by the plateau basalt layers, and almost perpendicular coulee walls locally notched by hanging valleys. Oesterich (1915) proposed that the hanging valleys resulted from glacial erosion of the coulee, but that the deepening of the coulee came about by enhanced fluvial erosion from the glacially enhanced and diverted Columbia River. He also recognized that the coulee was cut across a pre-glacial divide, which he correctly noted to lie just north of Coulee City.

An influential report was written by Oscar E. Meinzer, who later founded many of the hydrological science programmes of the US Geological Survey. Meinzer (1918) proposed that the glacially diverted Columbia River 'cut precipitous gorges several hundred feet deep, developed three cataracts, at least one of which was higher than Niagara . . . and performed an almost incredible amount of work in carrying boulders many miles and gouging out holes as much as two hundred feet deep'. He also recognized that the dipping surface to the basalt on the northern Columbia Plateau was important for generating a steep water-surface gradient to the Columbia River water that was diverted across the plateau by glacial blockage of its pre-glacial valley. The resulting increased velocity of the river water was thus capable of the enhanced erosion indicated by the scabland.

The Channeled Scabland

The cataclysmic flooding hypothesis for the origin of coulees on the Columbia Plateau centred on the work of J Harlen Bretz. Although formally introduced by papers in 1923 (Bretz 1923*a*, *b*), the idea of cataclysmic flooding causing the scablands was a certainly a matter of informal discussion before that time. McMacken (1937) credited the hypothesis to A. P. Tooth, of Lewis and Clark High School in Spokane, Washington. Bretz undoubtedly knew of this via his friend and benefactor, Thomas Large, also of Lewis and Clark High School. Nevertheless, Bretz (pers. commun. 1978) recalled that around 1909, while he was teaching high school science in Seattle, Washington, he became intrigued by an unusual landform on the newly published Quincy topographic sheet of the US Geological Survey. The map clearly showed the Potholes Cataract of the western Quincy Basin (Fig. 1). Bretz wondered how such a feature could have been formed without an obvious river course leading to it. His questions to geology faculty members at the University of Washington provided no satisfactory answer.

Bretz conducted extensive studies of the glacial geology of the Puget Sound region near Seattle, and in 1910 he left his high school teaching job to pursue graduate studies in glacial geology at the University of Chicago. Working with Professors R. D. Salisbury and T. C. Chamberlin, Bretz obtained his PhD in 1913, basing his dissertation on the Puget Sound glacial geology (Bretz 1913). After a 1-year appointment at the University of Washington, Bretz returned as a beginning faculty member at the University of Chicago. He began teaching field courses in geology, including an advanced summer course that he taught in the Columbia Gorge, where the Columbia River crosses the Cascade Range between Washington and Oregon.

One of Bretz's early papers derived from the Columbia Gorge fieldwork. It dealt with the widespread erratic boulders that were widely distributed in the region. Thomas Condon, University of Oregon, had earlier described these boulders, and also popularized the idea that they were rafted to their locations by berg ice during a marine submergence (Condon 1902, p. 62). He described the submergence of the Willamette Valley as an ocean sound, as follows:

> that fine old Willamette Sound . . . may in the days of the Mammoth and the Broad Faced Ox have welcomed to its scores of sheltered harbors, the ancient hunter who, in his canoe, if he had one, floated one hundred feet or more above the present altitude of the church spires of Portland and Salem.

Bretz (1919) proposed that the inundation of the lower Columbia River (Fig. 2) had been of freshwater, not marine water as advocated by Condon. Bretz reasoned that the immense discharge of the late Pleistocene Columbia River, swollen by glacial melt-water, had maintained the freshwater flow at a time of diastrophic movements that

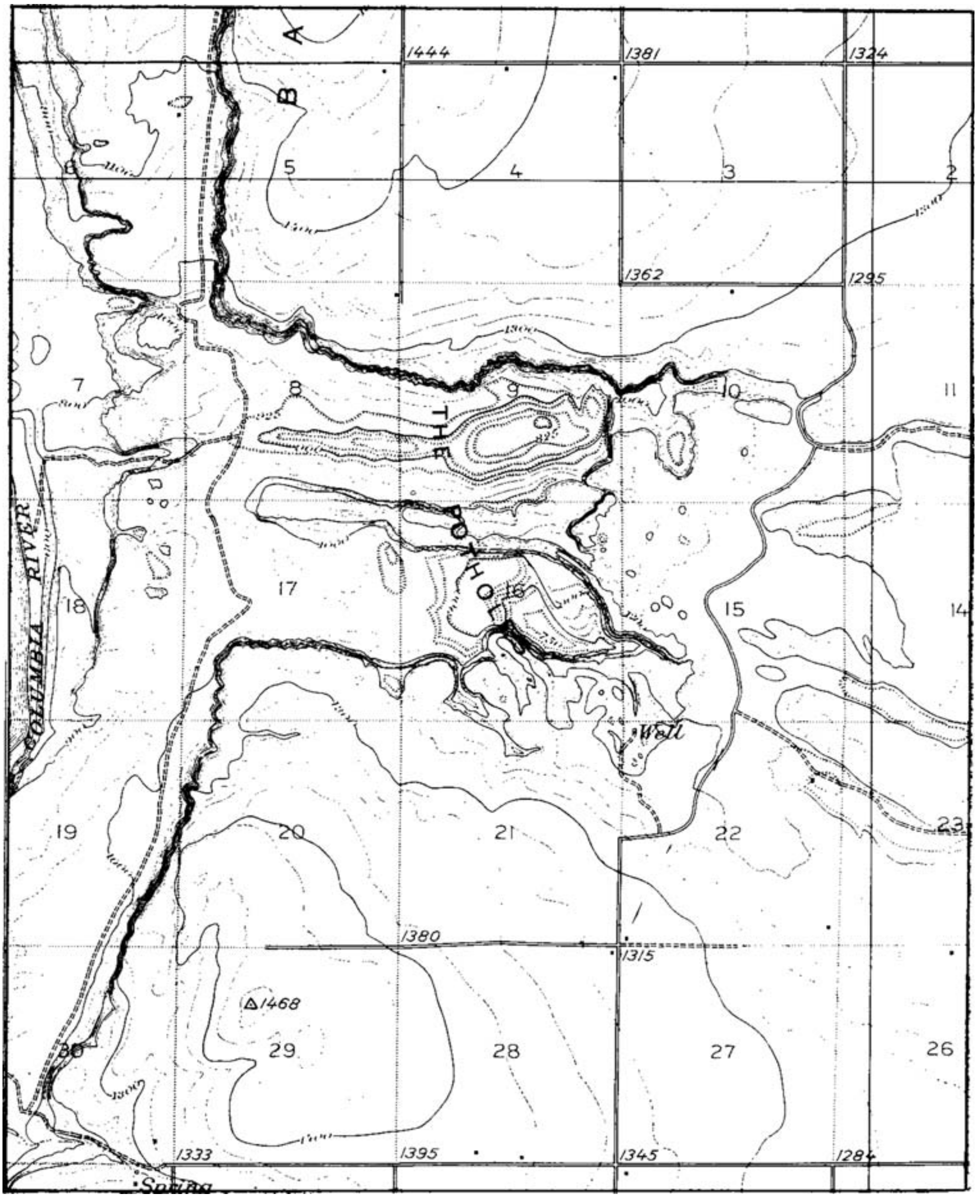

Fig. 1. Topographic map of the Potholes cataract, one of three cataract spillways on the west side of Quincy Basin in the channelled scabland. (From the US Geological Survey Quincy topographic quadrangle map, with 7.6 m-contour interval and 1.6 × 1.6 km numbered section squares).

otherwise would have led to submergence. Nevertheless, he found this explanation problematical in that the duration of ponding had been so brief that it did not create the expected shoreline features or lacustrine plains. The only evidences for the regional extent of ponding were isolated berg deposits and associated silts that Symons (1882) and Russell (1893) had ascribed to a Pleistocene 'Lake Lewis'. Moreover, Bretz could not find evidence of similar inundation or submergence in southwestern Washington State, where he would have expected the hypothetical diastrophism to have also operated. Finally, Bretz was concerned that other known examples of late Pleistocene

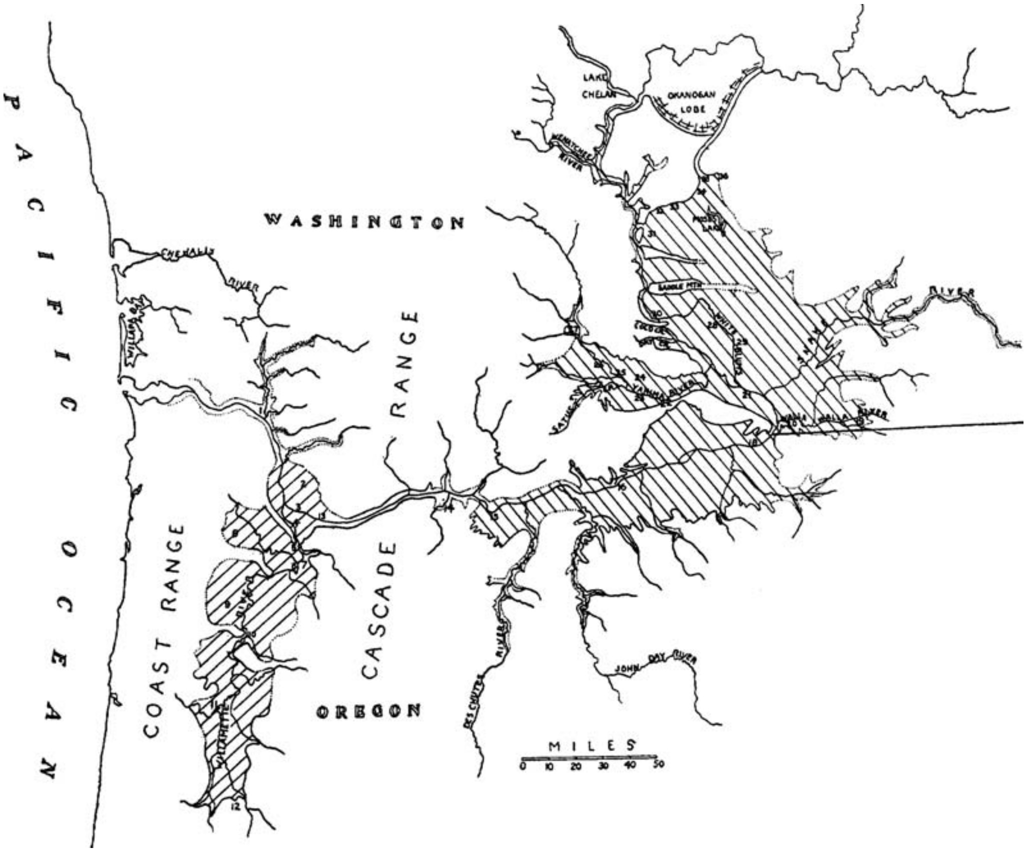

Fig. 2. Hypothesized submergence map of the lower Columbia River system, including the 'Willamette Sound' (NE to SW diagonal ruling) at about 120 m above modern sea level, and the area of 'Lake Lewis' (NW to SE diagonal ruling) at about 380 m above modern sea level (Bretz 1919). Ponded elevations were determined from the heights of ice-rafted erratic boulders.

submergence involved the invasion of marine waters into subsided areas from an immense glacial load had been removed by the rapid retreat of ice sheets. No such Pleistocene glacial load seems to have existed in the Columbia Gorge, yet an immense area (Fig. 2) had clearly been inundated by freshwater during the late Pleistocene.

Beginning in the summer of 1922, Bretz spent eight successive field seasons with parties of advanced geology student in areas of eastern Washington State upstream of the areas described in his 1919 paper. His first season of work led to a paper (Bretz 1923*a*) that was the text of on oral presentation made to the Geological Society of America on 30 December 1922. In that paper Bretz provided detailed descriptions of physiographical relationships in the region, noting the sharp distinction between the Palouse Hills of loess and the eroded tracts of scabland. Although Bretz (1923*a*) did not directly invoke cataclysmic processes, he did note that the indicated bedrock channel erosion required prodigious quantities of water. Referring to the three outlets at the south end of the Hartline Basin (Dry Coulee, Lenore Canyon and Long Lake Canyon), Bretz (1923*a*, pp. 593–594) stated that 'these are truly distributary canyons. They mark a distributive or braided course of the Spokane glacial flood over a basalt surface which possessed no adequate pre-Spokane valleys'. He also noted that the flows of the glacial melt-water transformed pre-glacial valleys into channels. Referring to Pine Creek valley, south of Spokane, Bretz (1923*a*, p. 584) wrote:

> The valley during this episode in its history was but a channel. The glacial stream filled it from side to side for a depth of tens of feet. This is shown a few miles above Malden, where the stream flooded over a low shoulder of basalt, cutting a channel in the rock at least 40 feet deep, though the main valley alongside was a wide open and received gravel deposits.

Bretz also recognized that the extent of removal of the Palouse loess cover, the scarps eroded into the loess and the steep gradients of the channel-ways were all important. He wrote (Bretz 1923*a*, p. 588):

> The scablands of the Palouse drainage, with channeled basalt deposits of stratified gravel, and isolated linear groups of Palouse Hills, their marginal slopes steepened notably, bear abundant evidence of a great flood of glacial waters from the north. This flood was born of the Spokane ice-sheet. Its gradient was high, averaging perhaps 25 feet to the mile, and it swept more than 400 square miles of the region clean of the weaker material constituting the Palouse Hills. The hills which have disappeared averaged 200 feet in height, and in some places the glacial torrents eroded 100 to 200 feet into the basalt.

The hypothesis of a truly catastrophic flood appeared in Bretz's second scabland paper (Bretz 1923*b*). In this paper Bretz also introduced the term 'channelled scablands' to refer to areas of loessial soil removal and fluvial scour into the underlying basalt rock. Bretz (1923*b*) provided the first detailed geomorphic map of the entire channelled scabland region, showing its overall pattern of anastomosing channel-ways. The paper also contained the first interpretation of the mounded scabland gravel deposits as subfluvially emplaced gravel bars. Great depths of water were indicated by the need to submerge these bars and by the indicated crossings of divide areas. He concluded (Bretz 1923*b*, p. 649) that '[i]t was a debacle which swept the Columbia Plateau'. The age of this flood, he reasoned, was tied to a glaciation that had occurred prior to the latest Pleistocene glaciation, known as the Wisconsin Glaciation. This older glaciation he named the Spokane Glaciation (Bretz 1923*a*), and its associated debacle was dubbed the Spokane Flood.

It may not be a coincidence that the second paper, with its potentially controversial advocacy of catastrophism, appeared shortly after two important events in Bretz's career: (1) he was promoted to the tenured rank of Associate Professor; and (2) he was named to the editorial board of the *Journal of Geology*, the journal in which the second paper appeared.

In a subsequent paper, Bretz (1924) described the process of subfluvial quarrying that could generate a scabland of anastomosing channels and rock basins cut into the basalt. The process was described for the modern Columbia River at The Dalles, Oregon, but he concluded that only large, vigorous streams could produce these landforms. Bretz (1925*a*, p. 144) then proposed a test of his cataclysmic flood hypothesis:

> A crucial test . . . is the character of the Snake and Columbia valleys beyond the scablands, for these valleys received all the discharge of the great glacial rivers . . .. If there is no evidence for a greatly flooded condition of these valleys then the hypothesis is wrong . . ..

Bretz (1925*b*) traced the Spokane Flood evidence downstream to the Snake and Columbia rivers (Fig. 3). Just below the confluence of those two rivers, where all the floodwaters from various scabland channels had to converge at the Wallula Gateway, he estimated the floodwater depth to be over 200 m above the modern river level. Flood depths of at least 120 m were maintained through the Columbia River gorge all the way to Portland, Oregon, where a huge flood delta was deposited over an area of 500 km^2, with bars over 30 m high on its surface. Bretz (1925*b*) also made the first estimate of the flood discharge, calculated at Wallula Gap using the Chezy Equation. The calculation was actually made by Bretz's colleague, D. F. Higgins, who found a discharge of nearly 2×10^6 m^3 s^{-1} (about 160 km^3 day^{-1}) and flow velocities of 10 m s^{-1}.

These phenomenal quantities of water led Bretz (1925*b*) to think about possible sources. Only two hypotheses seemed reasonable: (1) a very rapid and short-lived climatic amelioration that would have melted the Cordilleran Ice Sheet; or (2) a gigantic outburst flood induced by volcanic activity beneath the ice sheet. The latter phenomena were known to occur in Iceland, where they are known by the term 'jokulhlaup' (which Bretz spelled as 'jokulloup'). Bretz devoted much of the summer field season of 1926 to a search for the source of flooding. In an oral presentation at the Madison meeting of the Geological Society of America, 27 December 1926, Bretz (1927*a*, p. 107) concluded: 'Studies in Washington and British Columbia north of the scabland strongly suggest that basaltic flows which were extruded beneath the Cordilleran ice sheet produced the great flood'.

The Great Debate

The 'Great Scablands Debate' (Gould 1978) took place on 12 January 1927, at the 423rd meeting of the Geological Society of Washington, held at the Cosmos Club in Washington, DC. The entire meeting was devoted to the presentation and subsequent discussion of Bretz's talk, entitled 'Channeled Scabland and the Spokane Flood' (Bretz 1927*b*). In his presentation Bretz provided an overview of his hypothesis and a detailed listing of the numerous, otherwise anomalous phenomena that were explained by it. His talk was then followed by well-prepared criticisms from selected members of the audience, which consisted mainly of scientists from the United States Geological Survey.

W. C. Alden objected to: (1) the immense amounts of water ascribed to rapid melting of the ice sheet; and (2) the requirement that all the

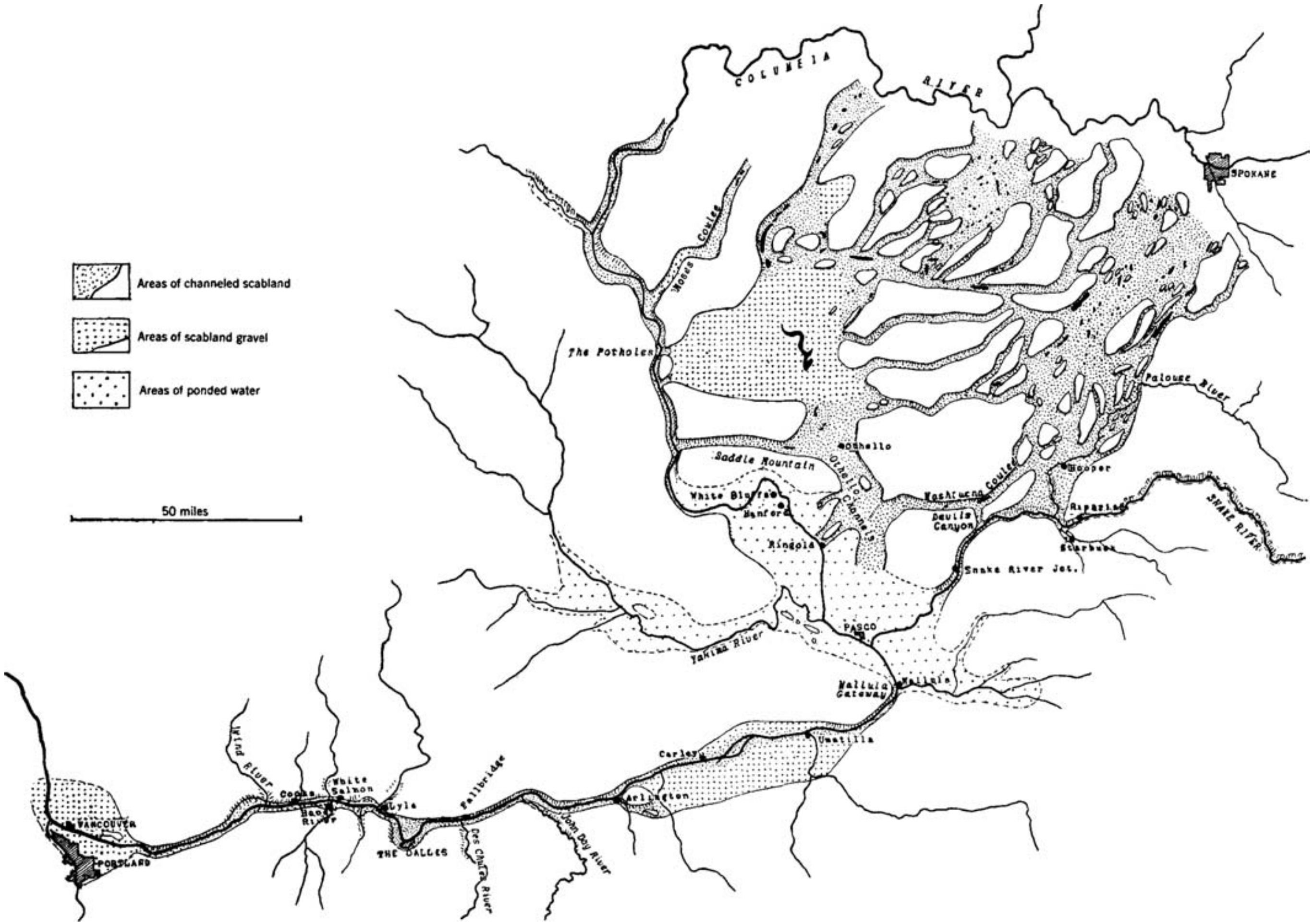

Fig. 3. Sketch map of regions affected by the Spokane Flood extending 500 km from Spokane, Washington, in the NE, to Portland, Oregon, in the SW (Bretz 1925*b*).

scabland channels developed simultaneously over a relatively short period of time. Although he had not visited the field areas, Alden believed these objections to be very serious. James Gilluly expanded on both of Alden's points with quantitative arguments that longer time periods needed to be involved than what Bretz had proposed. Moreover, he calculated that the indicated discharges of water could not be produced either by a climatic amelioration or subglacial volcanism. E. T. McKnight then raised specific objections about field relationships for coulees in the southern part of the scablands, and G. R. Mansfield objected to the rapid erosion of basalt by floodwaters.

Oscar E. Meinzer expanded upon ideas that he had proposed earlier (Meinzer 1918). He stated that the Columbia River, greatly swollen by glacial melt-water, could easily have carved Dry Falls and deposited the great gravel fan of the northern Quincy Basin. He interpreted the gravels of the Quincy Basin as constituting a series of terraces. The high-level crossing of divides could then be explained by successive abandonment as the Columbia progressively cut down to lower levels. Nevertheless, from past work (Schwennessen & Meinzer 1918) he realized that Bretz (1923*a*) was correct in that the four great spillways out of the Quincy Basin had floors at approximately equal elevation. However, instead of accepting Bretz's interpretation of coincident spillway operation during large-scale ponding of floodwater, Meinzer proposed that the spillways were cut one at a time, but that subsequent Earth movements later brought them to equivalent altitudes. Bretz (pers. commun. 1978) recalled that Meinzer first formulated this unusual hypothesis in response to a question that had Bretz asked him while he was defending his PhD thesis at the University of Chicago.

Bretz answered all these criticisms, both at the meeting itself (Bretz 1927*b*) and in subsequent papers. However, there was one, relatively minor comment to which Bretz did not reply. This concerned the effects of aspect on rates of talus accumulation, and it was made by J. T. Pardee, who earlier in the same summer as Bretz's first scabland field season had been sent by his supervisor Alden to study the scabland area SW of Spokane. Pardee (1922) reported in print that the area had been glaciated, but he provided few details and never published further results that were anticipated in his preliminary report. Bretz (pers. commun. 1978) suspected, from correspondence with Pardee in the 1920s, that the latter was considering a flood hypothesis for the origin of the scablands. Pardee (1910) had earlier documented the presence of an immense late Pleistocene lake in the western part of Montana. Named Glacial Lake Missoula, this lake had been impounded by the Cordilleran Ice Sheet, when it cut across the drainage of the modern Clark Fork River, which trends northwestward from western Montana. The lake held as much as 2000 km^3 of water, derived from melt-water inputs from surrounding glaciated areas.

Did Pardee suspect that his Glacial Lake Missoula had released an immense cataclysmic flood? If he did, Bretz surmised, his superior, Alden, had dissuaded him from the idea. Several years after the affair, David White, who was Alden's superior, showed Bretz a memorandum of 22 September 1922, in which Alden had written to White concerning Pardee's scabland studies: 'very significant phenomena were discovered in the region southwest of Spokane . . . . The results so far . . . require caution in their interpretation. The conditions warn against premature publication'. Also in 1922, correspondence between local Spokane residents Thomas Large and Barton W. Everman (Baker 1996*a*) indicated that Pardee informally told Everman that 'sub-glacial water erosion' involving water under pressure beneath ice was a possible hypothesis to explain the scabland erosion. Moreover, Pardee wrote to Bretz in 1925, suggesting that Lake Missoula be considered as a possible source for the Spokane Flood. In a 1926 letter to J. C. Merriam, Bretz wrote that Pardee proposed Lake Missoula as the Spokane Flood source, and that even Alden, 'our ultra-conservative in Pleistocene geology', agreed that fluvial processes were involved in the origin of the scablands.

Initially, Bretz seems to have resisted Pardee's suggestion of Glacial Lake Missoula as the source of the Spokane Flood. As noted above, he was intrigued by the possibility of subglacial volcanism. He also believed that Cordilleran ice had covered the area between the Lake Missoula ice dam and the heads of the scabland channels south of Spokane, a distance of 100 km. In 1927 he thought that the Spokane Flood was older than the latest Pleistocene glaciation that had formed Lake Missoula, and he also thought the Lake Missoula could not have supplied enough water to have inundated all the scabland channel ways. By 1928, however, Bretz resolved that the source of the Spokane Flood had to be Lake Missoula. Following attendance at Bretz's presentation of this idea at a scientific meeting, Harding (1929) published the first formal paper on this hypothesis without acknowledging either Bretz or Pardee as its source. Bretz made a more extensive presentation of the concept to the Geological Society of America annual meeting in Washington, DC, on 26 December 1929. In the published abstract of this paper, Bretz (1930*a*, p. 92) stated: '[i]t is suggested that bursting of the ice barrier which confined a large glacial lake among the mountains of western Montana suddenly released a very great quantity of water which escaped across the plateau of eastern Washington and eroded the channeled scablands'. In subsequent publications (e.g. Bretz 1932*a*), Bretz clearly illustrated the relationship of Glacial Lake Missoula to the Channeled Scabland.

After the Washington meeting, Bretz continued to answer in print the various criticisms of his Spokane Flood hypothesis (Bretz 1927*c*, 1928*b*). He added many specifics to hypothesis, including an extensive study of the scabland bars, with detailed descriptions, published in the *Bulletin of the Geological Society of America* (Bretz 1928*c*). An especially eloquent paper was published in *The Geographical Review* (Bretz 1928*a*), the journal of the American Geographical Society. The latter society also supported Bretz by publishing a handsome monograph on the Grand Coulee (Bretz 1932*a*). The results of Bretz's last field seasons, 1928–1930, were presented in papers concerned with valley deposits east and west of the Channeled Scabland (Bretz 1929, 1930*b*). He showed that these tributary valleys contained deposits that indicated emplacement by phenomenally deep floodwater that flowed up the tributaries, away from sources in the scabland channels. Along the Snake River, he traced these deposits to beyond Lewiston, Idaho, about 140 km upstream of the nearest scabland channel (Bretz 1929, p. 509):

> Up-valley currents of great depth and vigor are essential . . .. No descending gradient of the valley floor can be held responsible. The gradient must have existed in the surface of that flood. The writer, forced by the field evidence to this hypothesis, though warned times without number that he will not be believed, must call for an unparalleled rapidity in the rise of the scabland rivers.

Alternative hypotheses

The 1933 International Geological Congress field trip provided a kind of transition point in regard to the Spokane Flood controversy. Although Bretz successfully campaigned to include a field excursion to the Channeled Scabland, and even wrote the guidebook for that excursion (Bretz 1932*b*), he had to resign from leadership of the trip in order to participate in the Louise A. Boyd Greenland Expedition of the American Geographical Society. His substitute leader was Ira S. Allison of Oregon State College, who was sympathetic to the Spokane Flood hypothesis. Allison (1932) had even used it to explain landforms in the vicinity of Portland, Oregon. Although he subsequently developed his own hypothesis for the scablands (Allison 1933), he presented Bretz's views quite fairly during the field trip. Allison (pers. commun. 1978) recalled that the international audience of field- trip attendees included several famous geologists, including Alex Du Toit of South Africa and Edward Bailey of Scotland. They were very keen observers, who looked at the field evidence on their own, rather than waiting for the pronouncements of the field-trip leader. This was exactly the kind of scrutiny for his hypothesis that Bretz himself urged.

Allison's (1933) hypothesis was not a denial of the 'Spokane Flood,' but instead a modification of its details. He proposed that the critical factor in the flooding was not the immense volume of water, but instead the effects of floating berg ice. He presented compelling evidence, noted earlier in less detail by others (e.g. Condon 1902; Bretz 1919), that extensive Late Pleistocene ponding of water had occurred all the way from the Columbia River Gorge to Wallula Gap. The ponding was inferred to have arisen from blockage by ice of constricted reaches of the Columbia River in the gorge. The Columbia River, swollen by iceberg-rich melt-water, was impounded by this temporary dam until the inundation reached into eastern Washington. As the water rose to higher levels it spilled across secondary drainage divides, just as Bretz had inferred for the flooding. It thereby created the enigmatic hanging valleys/channel-ways, high-level gravel deposits and widely distributed erratic boulders. Allison's purpose in proposing this hypothesis was made clear by the concluding sentence in his paper: '[p]erhaps this revision will make the idea of such a flood more generally acceptable' (Allison 1933, p. 722).

Glacial hypotheses for the origin of the Channeled Scabland were proposed by several investigators. Charles Keyes, who published widely on many geological topics (he owned the journal *Pan American Geologist*), made a cursory inspection of the regional geography from topographic maps. His paper (Keyes 1935) concluded that both Moses Coulee and Grand Coulee had formed because of supra-glacial streams that had formed along the axes of the waning ice lobes of the Cordilleran Ice Sheet. These streams were then superimposed on the bedrock surfaces, thereby explaining their crossing of pre-glacial drainage divides. The explanation derived from a presumed analogy to late-glacial Laurentide Ice Sheet lobe in central Idaho, and it did not consider the morphology of bedrock erosion, giant gravel bars and other evidence of cataclysmic flooding.

E. T. Hodge of Oregon State College, Corvallis, was a fairly persistent critic of the Spokane Flood hypothesis, who gave numerous seminars and oral papers attacking it during the 1930s. His alternative explanation (Hodge 1934) was that the seemingly enigmatic features summarized by Bretz could all be explained by complicated alternation of ice advances and drainage changes. He argued that basalt could be quarried by glacial erosion during ice-sheet advances, and that channel complexes could derive their fluvial aspects from the diversion of melt-water streams around blocks of stagnant glacial ice and jams of berg ice that would result from glacial recessions. The published versions of this hypothesis were only presented in outline form as generalizations, and never contained detailed reference to actual field relationships.

Many of Hodge's criticisms were published from 1935 to 1937 as abstracts and notes in the *Geological Newsletter* of the Geological Society of the Oregon Country, which Hodge founded in 1935. The society was apparently founded in part because of a dispute arising from an invitation extended to Bretz to speak on the Spokane Flood at a scientific meeting in Pullman, Washington. Bretz (pers. commun. 1978) recalls that Hodge was so incensed at the invitation that he wrote to the chairman of the meeting demanding that he be allowed to formally debate Bretz after the invited address. When this was refused, Hodge founded his society in order to have it meet concurrently in Pullman. Bretz eventually acceded to an informal debate with Hodge on the day following his formal presentation. After Hodge began the debate with another retelling of his glacial hypothesis, Bretz responded with the suggestion that any interested parties should simply drive out across the Palouse Hills from Pullman to the nearby Cheney–Palouse scabland tract, and look at the field evidence. En route Bretz demonstrated, with an ordinary kitchen colander, how above a certain elevation the loess consisted of silt only, but below that level, in scarps near the scabland tracts, granules and pebbles of basalt and erratic granite indicated that the water flows 30 m deep or more were responsible for their deposition. At the former Palouse–Snake divide, subsequently crossed by floodwater, Bretz pointed out giant gravel bars, prow-pointed hills of loess, abandoned cataracts and spectacular scabland erosion. Thus, the point was made that the field evidence, not Bretz's rhetoric, was the rebuttal to his critics.

Another glacial hypothesis was proposed by the eminent glacial geologist W. H. Hobbs, University of Michigan. Hobbs (1947) stated that he was stimulated in his study by a map of the Channeled Scabland presented during a lecture on evidence for the Spokane Flood. He immediately recognized in the pattern of scabland erosion and the nearby loess accumulation a pattern that he believed to be associated with large ice sheets, like that of Greenland, for which he had made extensive observation. With grants from the Geological Society of America and the American Philosophical Society, Hobbs spent two field seasons attempting to prove his initial hypothesis. He proposed that a lobe of the Cordilleran Ice Sheet, which he named the 'Scabland Glacial Lobe', had occupied much of the Channeled Scabland (Hobbs 1943). This lobe had eroded much of the scabland topography, while the anticyclonic winds blowing off it had deposited the adjacent loess of the Palouse Hills. Most of the scabland gravel deposits, he proposed, were moraine remnants that had been modified by glacier-border drainage. Although it was presented orally at meetings of the Geological Society of America (Hobbs 1945), the full manuscript exposition this hypothesis was rejected for publication during successive peer reviews by both of the professional societies that had sponsored the research. The manuscript was subsequently printed privately (Hobbs 1947) and distributed by its author.

The most serious challenge to the Spokane Flood hypothesis was posed by Richard Foster Flint of Yale University. Flint had a brief association with Bretz, who served on Flint's PhD examining committee at the University of Chicago in 1925, when Bretz was an associate professor. The two men had very different personalities, which seem to have influenced their approaches to science. Both men worked in the rapidly advancing subject of glacial geology, and Flint eventually became known for writing the most widely used textbooks in the field (Flint 1947, 1957, 1971).

Some of Flint's early research at Yale was focused on the Connecticut River valley ice-stagnation features, associated with the Late Pleistocene ice sheet that had covered New England (Flint 1928, 1932). Interestingly, these same features had been extensively studied by the famous Yale geologist James Dana, who had interpreted them to be evidence of an immense flood that had emanated from the glacial margin (Dana 1882). Flint achieved part of his early reputation by showing that his famous Yale predecessor had been wrong in arguing for a cataclysmic flood origin of the Connecticut valley landforms.

One of Flint's colleagues at Yale, Aaron Waters, recalled (pers. commun. 1978) suggesting to Flint that he would find more interesting examples of ice stagnation on the Waterville Plateau of eastern Washington, where the dry climate meant that landforms were not obscured by vegetation. This is the area where the Okanogan Lobe of the Cordilleran Ice Sheet had advanced across the northwestern Columbia Plateau, blocking the Columbia River valley, thereby diverting its flow and/or any cataclysmic flooding across the plateau in into the Channeled Scabland. During the 1930s Flint published several papers on the glacial features of the region (Flint 1935, 1936, 1937). Waters (pers. commun. 1978), who had been born on the Waterville Plateau, recalled being so incensed by Flint's publications that he initiated his own studies of glacial features in the region. Waters (1933) proposed a cataclysmic flood origin for landforms along the Columbia River downstream of the impoundment created by the Okanogan Lobe, which presumably failed to generate the flood. Flint (1935) disputed Waters' interpretation. Eventually, Waters' growing interest in volcanic geology and his involvement in World War II intervened with his geomorphological research programme so that he never completed his flood-related research.

Flint (1938*a*, p. 463) described his entry into the Spokane Flood controversy as follows:

> I have had the opportunity to examine . . . this system during three field seasons' study . . .. During that time it gradually became apparent that the published explanations of the genesis of these drainage ways did not meet the requirements of the field data as I saw them, and, accordingly, a fourth season (Summer, 1936) was devoted to an intensive examination of one of the principal drainage tracts of the complex.

His paper presented many detailed field descriptions to make the case that the Cheney–Palouse scabland tract, easternmost in the channelled scabland, was the product of 'leisurely streams with normal discharge' (Flint 1938*a*, p. 472). Flint also enhanced his growing international reputation by the publication of a German-language version of his Cheney–Palouse paper (Flint 1938*b*).

Flint (1938*a*) accepted Bretz's (1923*b*, 1928*c*) observations that scabland fluvial gravel often: (1) occurred in the lee of island-like areas; (2) had rounded upper surface morphologies; and (3) exhibited a parallelism of surface slopes with the dip of underlying fore-set bedding. Nevertheless, he proposed these 'bar-like' morphologies were merely the expressions of 'non-paired, stream-cut terraces in various states of dissection' (Flint 1938*a*, p. 475). It was an idea that Bretz (1923*a*) had briefly entertained, then rejected after further field examination (Bretz 1923*b*, 1928*c*). Flint ascribed the dissection to a downstream base-level reduction. Terrace remnants were preferentially preserved in the lee of island-like areas. The low precipitation of the region and the high infiltration capacity of the gravel alluvium prevented gulleying, so that the terrace remnants developed rounded 'bar-like' slopes by dry creep. Flint also found places where the surfaces of the deposits did indeed truncate their internal forest bedding.

Flint (1938*a*) traced the coarse-grained Cheney–Palouse scabland deposits downstream into the Pasco Basin, where he inferred that the deposits changed in facies from sand and gravel to silt and fine sand containing erratic stones. He named this fine-grained facies the 'Touchet beds'. These deposits had already been described by Bretz (1929, pp. 516–536; 1930*b*, p. 414), who ascribed them to Spokane Flood water hydraulically ponded upstream of the Wallula Gateway, and by Allison (1933), who ascribed them to normal pro-glacial runoff impounded by ice jams. Flint (1938*a*) proposed that the damming was provided by a landslide or glacial ice in the Columbia Gorge, as earlier suggested by Russell (1893). Following Symons (1882), Flint named the resulting water body 'Lake Lewis' (see Fig. 1).

At this point Flint had the necessary components for his alternative to the Spokane Flood hypothesis. First, the pro-glacial melt-water streams of normal discharge overran the northern margin of the Cheney–Palouse tract (diagram 1 in Fig. 4). However, as Lake Lewis formed downstream, the 'leisurely' scabland streams aggraded, forming a thick fill (diagram 2 in Fig. 4). This fill blocked pre-glacial tributaries to the scabland tracts, forming marginal lakes that accumulated fine-grained sediments, while the main streams shifted laterally to cut scarps in the loess hills bounding the scabland valleys (diagram 3 in Fig. 4). Finally, when Lake Lewis drained, the streams gradually incised into the fill, thereby forming non-paired terrace remnants, some of which resembled 'bars' (diagram 4 in Fig. 4). Moreover, the enigmatic notched spurs and slot-like hanging valleys crossing divides could all result from superposition of normal streams from the widespread fill, instead of being eroded by the spilling of Spokane Flood water across divides when the pre-glacial valleys could not convey its cataclysmic discharges.

Flint's argument that relatively small streams could cut produce scabland-like erosion in rock was based on examples along the Snake River in Idaho. He correctly noted the presence of scabland landforms near Twin Falls, Idaho, where the Snake flows in a deep, narrow canyon (Flint 1938*a*, p. 492):

> The . . . [basalt] flows yielded to the hydraulic force of the Snake River as similar flows on the Columbia Plateau yielded to the hydraulic force of proglacial streams, yet I am not aware that unusual floods have been held to have affected the upper Snake River.

This line of argument fell into disfavour when Malde (1968) demonstrated that the area was intensely scoured by another cataclysmic flood, the late Pleistocene overflow of Lake Bonneville. The latter was quite similar in its dynamics to Bretz's scabland flooding (O'Connor 1993).

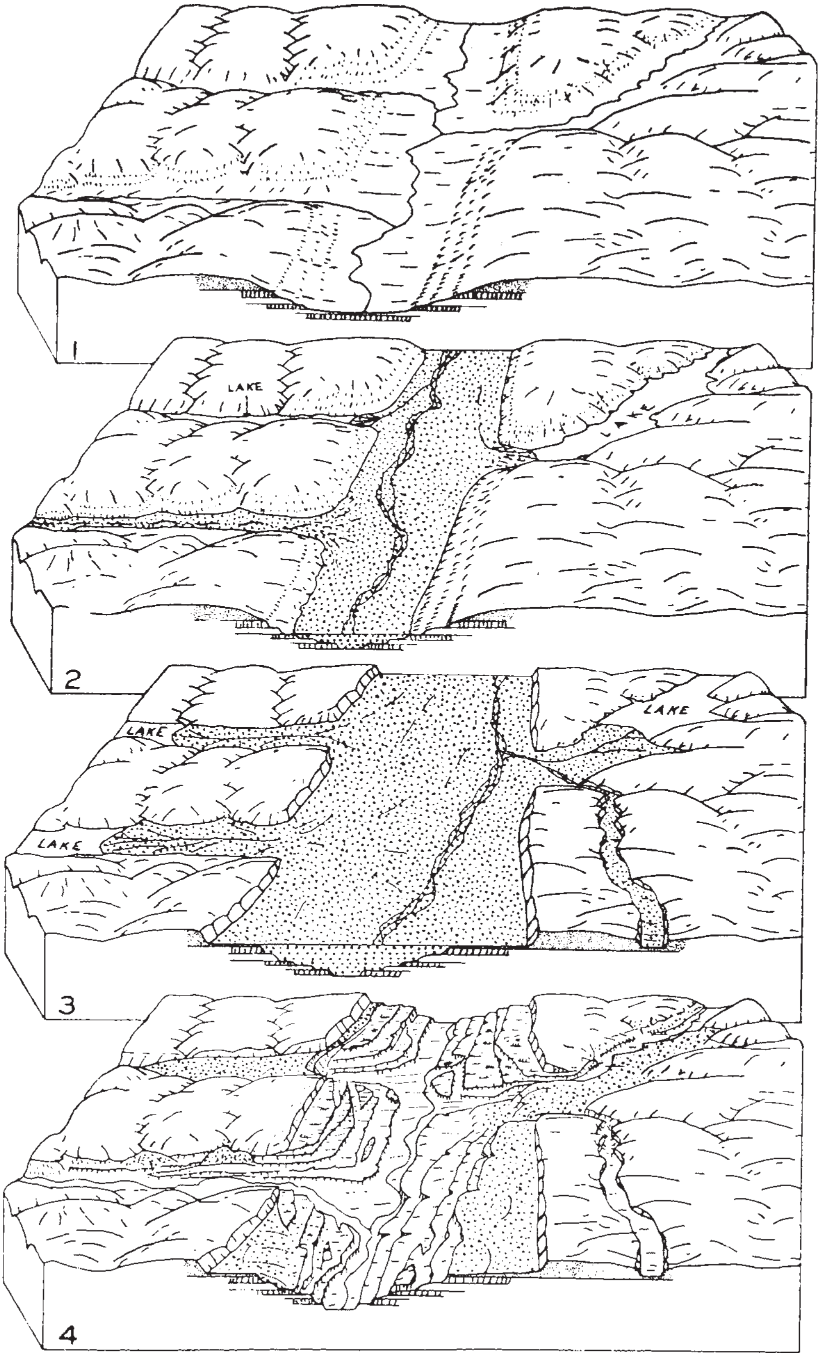

Fig. 4. Diagrams illustrating Flint's fill hypothesis for the origin of a scabland tract (Flint 1938*a*): (1) normal pre-glacial valleys with tributaries eroded into the nearby Palouse loess hills; (2) melt-water stream from nearby glacier front has aggraded the scabland valley floor and begun to backfill tributaries (stippled pattern); (3) many tributaries are completely backfilled, and the main valley stream has migrated to cut scarps on the bordering loess hills; and (4) fluvial dissection has eroded into bedrock and left remnants of the formerly extensive fill, some of which resemble 'bars', and also produced 'divide crossings' by superimposition across spurs.

Resolution

The beginning of change in the mostly skeptical reaction to the Spokane Flood hypothesis came during the course of another scientific meeting. Ironically, however, unlike the 1927 Geological Society of Washington meeting ('Great Scablands Debate'), Bretz was not in attendance. On 17–23 June 1940, the American Association for the Advancement of Science (AAAS) met in Seattle. The association's geological section included a session, 'Quaternary Geology of the Pacific Northwest', held in the afternoon of Tuesday 18 June. The session paper titles suggested that non-cataclysmic origins of the Channeled Scabland would be advocated. A post-meeting field trip to the Channeled Scabland was led by Flint. Although Bretz had been invited to attend, he declined, replying that all his ideas and supporting evidence were in print. If critics would just pay attention to the field evidence, it would speak for itself.

The early papers in the AAAS session merely reiterated the various alternatives for the origin of the Channeled Scabland. Hodge (1940) provided yet another retelling of his generalized scenario involving glacial erosion and complex damming and diversion of melt-water streams. Allison (1940) provided a critique of Flint's fill hypothesis, contrasting it with his own ice-jam theory. In a subsequent, more extended article, Allison (1941) outlined what he believed to be the key shortcomings with regard to Flint's hypothesis. First, Flint's (1938*a*) 'leisurely streams with normal discharge' were completely inadequate to explain the field evidence of anastomosing scabland channels and rock basins, all eroded deeply into bedrock. Second, the scabland gravels were not contemporaneous with the Touchet Beds of Flint's 'Lake Lewis,' proposing instead that the Touchet lacustrine sequence was younger than the gravels, and therefore unrelated genetically to them. Finally, Allison agreed with Bretz that the mounded gravels and other peculiar shapes of scabland erosional and depositional landforms required shaping by extraordinary fluvial processes. Nevertheless, he still held that such processes could be generated by the action of ice, leading to the complex jamming of various channel ways.

The surprise of the 1940 AAAS meeting came from an unexpected source. A meeting attendee, Howard A. Meyerhoff (pers. commun. 1978), related that no one in attendance expected that any speaker would directly support Bretz's Spokane Flood hypothesis. The eighth speaker of the session was Joseph Thomas Pardee, whose paper was entitled 'Ripple marks (?) in glacial Lake Missoula' (Pardee 1940). Pardee, who apparently was not a dynamic speaker, quietly described Camas Prairie, an intermontane basin in northwestern Montana. On the floor of this basin were ripple marks, composed of coarse gravel and exhibiting a size that was 'extraordinary'. These ripples were up to 15 m high, and were spaced up to 150 m apart (Fig. 5). The ripples had formed in a great ice-dammed lake, Glacial Lake Missoula, which Pardee (1910) had earlier documented to cover an immense area in western Montana. This late Pleistocene lake had held about 2000 km^3 of water, and it was impounded to a maximum depth of about 600 m behind a lobe of the Cordilleran Ice Sheet occupying what is now the modern basin of Lake Pend Oreille that in northern Idaho. In his presentation, and in a subsequent extended paper (Pardee 1942), Pardee presented his new evidence that the ice dam for Glacial Lake Missoula had failed suddenly, with a resulting rapid drainage of the lake. Evidence for the latter included the ripple marks, plus severely eroded constrictions in lake basins and giant gravel bars of current-transported debris. Some of the latter accumulated in high eddy deposits, marginal to the lake basins, and showing that the immensely deep lake waters were rapidly draining westward.

Remarkably, Pardee ended his paper at that point, without saying where the immense flood of 2000 km^3 of water, 600 m deep at its breakout point, would eventually go as it entered the Columbia River system in northeastern Washington. Nevertheless, the obvious connections to the Channeled Scabland and the Spokane Flood were made by members of the audience in the formal discussion that followed Pardee's paper. A group of 34 participants from the meeting, but not including Pardee, then attended an extended field excursion, 1 day of which was devoted to the scablands. Richard Foster Flint, who had not attended the session with Pardee's paper, joined the group to lead the scabland field visit. To his surprise, at each of the stops he had chosen to illustrate his hypothesis for scabland origins, Flint found that many of the trip participants, notably Aaron Waters, countered the Flint story with well-reasoned cataclysmic flood explanations, all of which were firmly tied to a source at Pardee's Lake Missoula.

Pardee retired from the US Geological Survey on his 70th birthday: 30 May 1941. The manuscript of his 1942 paper was submitted to the Geological Society of America several months later. This timing ensured that the paper would not have to pass the required formal review by Alden, Pardee's former supervisor, who was also a long-time critic of the cataclysmic flood hypothesis.

In the summer of 1952, Bretz returned to the Channeled Scabland for an intensive programme of field investigations. The purpose was to use

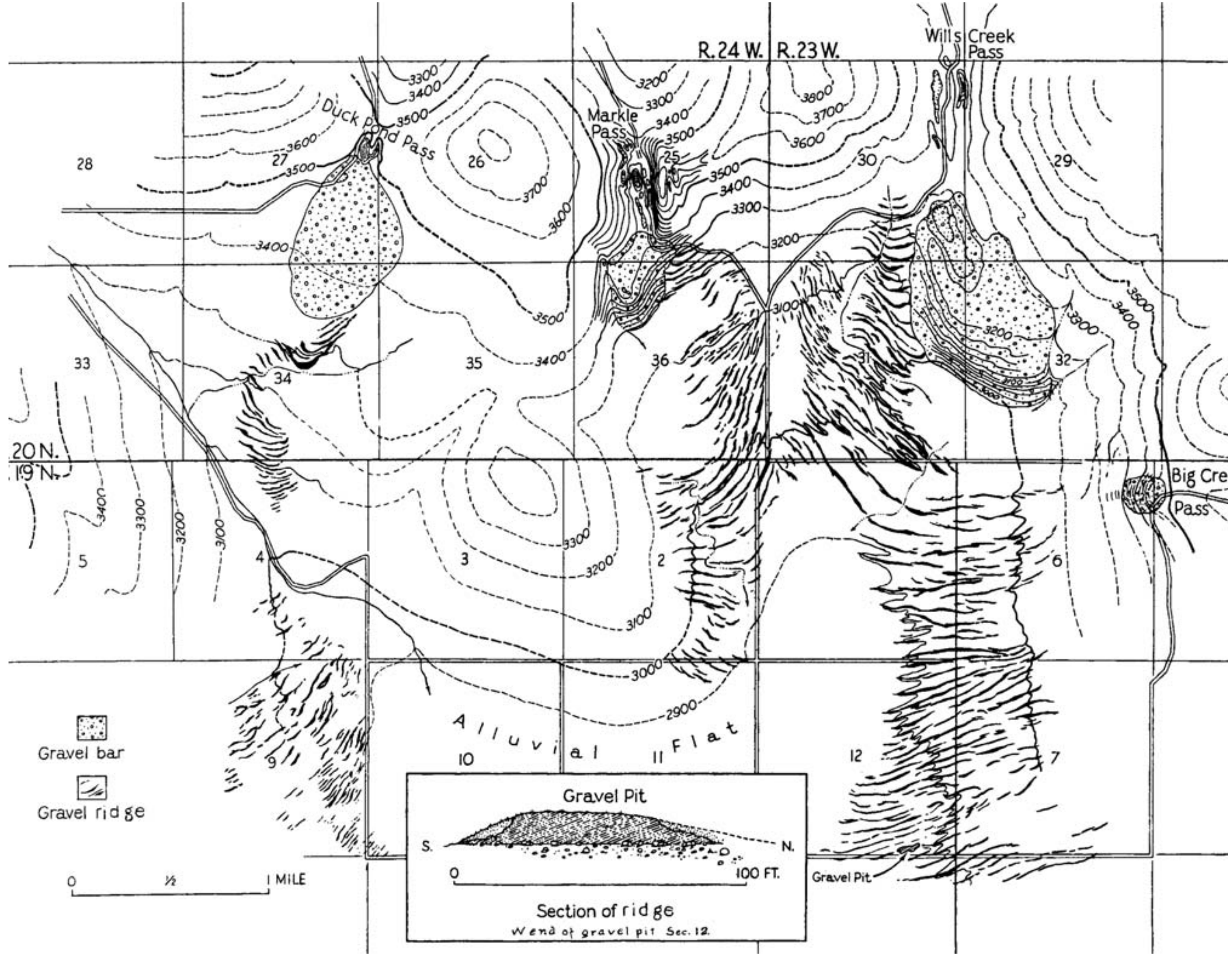

Fig. 5. Map of giant current 'ripple marks' in the northern part of Camus Prairie Basin of Glacial Lake Missoula (Pardee 1942).

new data that had been obtained through surveys for the Columbia Basin Irrigation Project of the United States Bureau of Reclamation. In this new work, Bretz was joined by George E. Neff of the Bureau of Reclamation, and by Professor H. T. U. Smith, University of Massachusetts, who was obliged to act as a 'skeptic for all identifications and interpretations' (Bretz *et al.* 1956, p. 761). In an obvious reference to Chamberlin's (1890) 'multiple working hypotheses' method, Bretz *et al.* (1956, p. 960) stated that: '[t]he field work was carried out with three men working together as a check on the "ruling-theory" tendency'. This new study was supported by a grant from the Geological Society of America. Bretz also received encouragement from several prominent geologists, among them: (1) Waters, who advised, 'the best thing you can do to convince your reader is to beg, cajole, even browbeat him into *really looking* at the region's topographic maps'; and (2) fluvial geomorphologist J. Hoover Mackin, who said: 'to understand the scabland, one must throw away textbook treatments of river work' (Bretz *et al.* 1956, p. 960).

The published results of the new study (Bretz *et al.* 1956) contain an immense amount of data. Excavations from the irrigation project and new topographic maps all showed that the gravel hills interpreted as bars by Bretz (1928*c*) were indeed subfluvial depositional bed forms of immense scale. Most convincing of all was the presence of giant current ripples on many of these bar surfaces. At Staircase Rapids Bar, for example, the new maps and photographs showed an extensive set of these ripples on the surface that Flint (1938*a*, p. 486) had specifically described as a river terrace.

The 1956 paper and subsequent elaborations (Bretz 1959, 1969) successfully countered all opposition to the cataclysmic flood origin of the Channeled Scabland, and the original hypothesis was also extensively modified. It was no longer 'the Spokane Flood', but instead became the Missoula Floods (Bretz 1969). Nevertheless, there was a lingering suspicion that one was dealing with an unusual exception to a general rule. Bretz (1928*a*, p. 119) had himself claimed: 'The unique assemblage of forms . . . described here as the channeled scabland . . . records a unique episode in Pleistocene history . . .. Special causes seem clearly indicated'. Standard textbooks continued to treat the topic as controversial (Thornbury 1969). In the most widely used textbook on glacial and Quaternary phenomena, perhaps the most spectacular ice-age phenomenon was accorded but a single sentence, as follows (Flint 1971, p. 232): 'Similar features, collectively known as channelled scabland, were widely created east of the Grand Coulee by overflow of an ice-margin lake upstream'. Nevertheless, a succession of studies developed Bretz's insights into the cataclysmic flood (e.g. Trimble 1963; Richmond *et al.* 1965; Malde 1968; Baker 1973, 1974, 1981). Bretz outlived most of his critics (Fig. 6) and by the 1980s the controversy shifted from whether cataclysmic flooding had occurred

Fig. 6. Professor J Harlen Bretz (left) at his home with Victor R. Baker (right). Photographed in 1977 by Rhoda Riley.

in the channelled scabland to: (1) how many cataclysms were involved (Baker & Bunker 1985; Waitt 1985); and (2) how the general processes of cataclysmic flooding impacted other regions, both on Mars (Baker 1978, 1982) and on Earth (Baker *et al.* 1993).

Implications

During the intense debates over the Spokane Flood, Bretz held to a particular view of how hypotheses function in the Earth sciences. He wrote (Bretz 1928*b*, p. 701):

> Ideas without precedent are generally looked on with disfavor and men are shocked if their conceptions of an orderly world are challenged. A hypothesis earnestly defended begets emotional reaction which may cloud the protagonist's view, but if such hypotheses outrage prevailing modes of thought the view of antagonists may also become fogged.
>
> On the other hand, geology is plagued with extravagant ideas which spring from faulty observation and misinterpretation. They are worse than 'outrageous hypotheses,' for they lead nowhere. The writer's Spokane Flood hypothesis may belong to the latter class, but it cannot be placed there unless errors of observation and direct inference are demonstrated.

The reference to an 'outrageous hypothesis' derives from a 1925 address delivered by William Morris Davis, and subsequently published with the title 'The value of outrageous geological hypotheses,' in which he claimed (Davis 1926, p. 464): '[w]e shall indeed be fortunate if geology is so marvelously enlarged in the next thirty years as physics has been in the last thirty. But to make such progress violence must be done to many of our cherished principles'. Davis was not so much looking to the proposing and testing of hypotheses as he was to having a serious engagement with them (Davis 1926, pp. 467–468):

> The idea is set forth simply as an outrage, to do violence to certain generally established views about earth's behavior that perhaps do not deserve to be regarded as established; and it is set forth chiefly as a means of encouraging the contemplation of other possible behaviors; not, however, merely a brief contemplation followed by an off-hand verdict of 'impossible' or 'absurd,' but a contemplation deliberate enough to seed out just what conditions would make the outrage seem permissible and reasonable.

According to the discredited philosophy of logical positivism (which was falsified by its own criteria through the efforts of its own adherents), science (for which the logical positivists took physics as their model) advances by logical propositions and their experimental verification. The latter criterion was modified to falsification, and more complex criteria have been devised by the various analytical philosophical successors to logical positivism. That much of this is of little relevance to classical geology has been argued elsewhere (Baker 1996*b*, 2000). William Whewell, one of the few philosophers of science to have had any familiarity with geology, suggested from his historical studies of science that the validity of hypotheses (we would now say their productivity or fruitfulness for inquiry) was demonstrated by their ability to bring together *disparate* observations under an overarching explanation and to produce explanatory surprises, such that previously unknown phenomena are also found to fit under that explanation (Whewell 1840) – a procedure that he called 'consilience of inductions' (which involved a kind of coherence theory of truth). Hypotheses are not mere propositions to be tested. They are 'working' elements of inquiry, intimately connected to the phenomena that they explain, and are subject to modification.

The idea that the Spokane Flood hypothesis explains an entire assemblage of features was pervasive throughout Bretz's papers. In an oral meeting presentation on scabland bar morphologies, size, composition, internal structure (fore-set bedding) and distribution on the land surface (including on the summits of prominent pre-glacial divides), Bretz (1928*d*, p. 160) concluded:

> The hypothesis of a 'Spokane Flood' alone seems capable of explaining the assemblage. Various alternatives proposed by others or constructed by the author have uniformly failed to explain the field evidence.

Another component of Bretz's reasoning was that a geological hypothesis is not merely tested against the existing data. Rather, the hypothesis is used as a guide to further field study. This is, of course, the 'working' component of Chamberlain's (1890) conception of 'hypothesis'. Bretz (1930*b*, p. 386) made this point as follows:

> The flood hypothesis was not to stand or fall on data then in hand ... it could be critically tested by further field study. Certain relationships in unexamined areas must exist if it were incorrect ....

What is discovered in the course of that 'further field study' is to be judged for consistency with the original hypothesis, or its subsequent modification. Moreover, that judgement is not up to the hypothesizer; it is instead a matter for the larger science community that is dedicated to the truth in this matter. Bretz (1930*b*) also refused to separate the act of hypothesizing from the data collection used to test the hypothesis. Instead, he claimed (Bretz 1929, p. 541):

> The final accepted explanation for channeled scabland must be built on, limited by, and constructed to include, all the field evidence .... The data in this paper constitute a category of facts not known when the flood hypothesis was first proposed. The relations to that hypothesis are to be decided by the reader. The writer asks only that, if his interpretation be rejected,

the date herewith presented be organized to make some coherent explanation.

In all of these attitudes toward his hypothesis, Bretz was following pragmatic practices that had been promoted by his fellow geologists (e.g. Gilbert 1886; Chamberlin 1890; Davis 1926). The philosophical bases for these practices require exposition beyond the limits of this paper, but they can be found in Baker (1996*b*, *c*, 1998, 1999*a*, *b*, 2000).

The differences in attitude between Bretz and his critics or competitors were often subtle. Like Bretz, many of the latter were honestly searching for an explanation for the scabland phenomena. Nevertheless, unlike Bretz, they committed the No. 1 error for pragmatic inquiry: they placed an artificial limitation on that inquiry. 'Do not block the way of inquiry' is absolutely essential to all reasoning (Peirce 1992). The limitation imposed by Bretz's critics was the version of uniformitarianism promoted by Charles Lyell and others, to the detriment of sound geological inquiry (Baker 1998). Bretz was under no such limitation. Shortly before his death, upon receiving the 1979 Penrose Medal, the highest honour of the Geological Society of America, Bretz (1980, p. 1095) wrote, in his acceptance, and last published work: 'Perhaps I can be credited with reviving and demystifying legendary catastrophism and challenging a too rigorous uniformitarianism'.

I thank the late J Harlen Bretz for enthusiastic communications, interviews and insights that greatly aided both my own early studies of cataclysmic flooding and also my exploration of the historical dimensions to the controversy for which his contributions played such a pivotal role.

References

ALLISON, I. S. 1932. Spokane Flood south of Portland, Oregon. *Bulletin of the Geological Society of America Bulletin*, **43**, 133–134.

ALLISON, I. S. 1933. New version of the Spokane Flood. *Bulletin of the Geological Society of America*, **44**, 675–722.

ALLISON, I. S. 1940. Flint's fill hypothesis of origin of scabland. *Bulletin of the Geological Society of America*, **51**, 2016.

ALLISON, I. S. 1941. Flint's fill-hypothesis for channeled scabland. *Journal of Geology*, **49**, 54–73.

BAKER, V. R. 1973. *Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington*. Geological Society of America, Special Paper, **144**.

BAKER, V. R. 1974. Erosional forms and processes for the catastrophic Pleistocene Missoula floods in eastern Washington. *In*: MORISOWA, M. (ed.) *Fluvial Geomorphology*. State University of New York, Binghamton, New York, 123–148.

BAKER, V. R. 1978. The Spokane Flood controversy and the Martian outflow channels. *Science*, **202**, 1249–1256.

BAKER, V. R. (ed.). 1981. *Catastrophic Flooding: The Origin of the Channeled Scabland*. Dowden, Hutchinson & Ross, Stroudsburg, PA.

BAKER, V. R. 1982. *The Channels of Mars*. University of Texas Press, Austin, TX.

BAKER, V. R. 1996*a*. Joseph Thomas Pardee and the Spokane Flood controversy. *GSA Today*, **5**, 169–173.

BAKER, V. R. 1996*b*. Hypotheses and geomorphological reasoning. *In*: RHOADS, B. L. & THORN, C. E. (eds) *The Scientific Nature of Geomorphology*. Wiley, New York, 57–85.

BAKER, V. R. 1996*c*. The pragmatic roots of American Quaternary geology and geomorphology. *Geomorphology*, **16**, 197–215.

BAKER, V. R. 1998. Catastrophism and uniformitarianism: logical roots and current relevance in geology. *In*: BLUNDELL, D. J. & SCOTT, A. C. (eds) *Lyell: The Past is the Key to the Present*. Geological Society, London, Special Publications, **143**, 171–182.

BAKER, V. R. 1999*a*. The methodological beliefs of geologists. *Earth Sciences History*, **18**, 321–335.

BAKER, V. R. 1999*b*. Geosemiosis. *Bulletin of the Geological Society of America*, **111**, 633–646.

BAKER, V. R. 2000. Conversing with the Earth: the geological approach to understanding. *In*: FRODEMAN, R. (ed.) *Earth Matters: The Earth Sciences, Philosophy, and the Claims of Community*. Prentice-Hall, Englewood Cliffs, NJ, 1–10.

BAKER, V. R. & BUNKER, R. C. 1985. Cataclysmic Late Pleistocene flooding from glacial Lake Missoula: A Review. *Quaternary Science Reviews*, **4**, 1–41.

BAKER, V. R., BENITO, G. & RUDOY, A. N. 1993. Paleohydrology of late Pleistocene superflooding, Altay Mountains, Siberia. *Science*, **259**, 348–350.

BAULIG, H. 1913. Le plateaux del lave du Washington central et la Grand 'Coulee'. *Annales géographie*, **22**, 149–159.

BRETZ, J. H. 1913. *Glaciation of the Puget Sound Region*. Washington Division of Mines and Geology, Bulletin **8**.

BRETZ, J. H. 1919. The late Pleistocene submergence in the Columbia Valley of Oregon and Washington. *Journal of Geology*, **27**, 489–505.

BRETZ, J. H. 1923*a*. Glacial drainage on the Columbia Plateau. *Bulletin of the Geological Society of America*, **34**, 573–608.

BRETZ, J. H. 1923*b*. The Channeled Scabland of the Columbia Plateau. *Journal of Geology*, **31**, 617–649.

BRETZ, J. H. 1924. The Dalles type of river channel. *Journal of Geology*, **32**, 139–149.

BRETZ, J. H. 1925*a*. Spokane Flood beyond the channeled scablands. *Bulletin of the Geological Society of America Bulletin*, **36**, 144.

BRETZ, J. H. 1925*b*. The Spokane Flood beyond the channeled scablands. *Journal of Geology*, **33**, 97–115, 236–259.

BRETZ, J. H. 1927*a*. What caused the Spokane Flood? *Bulletin of the Geological Society of America*, **38**, 107.

BRETZ, J. H. 1927*b*. Channeled Scabland and the Spokane. *Journal of the Washington Academy of Sciences*, **17**, 200–211.

BRETZ, J. H. 1927*c*. The Spokane Flood: a reply. *Journal of Geology*, **35**, 461–468.

BRETZ, J. H. 1928*a*. Channeled Scabland of eastern Washington. *Geographical Review*, **18**, 446–477.

BRETZ, J. H. 1928*b*. Alternative hypotheses for channeled scabland. *Journal of Geology*, **36**, 193–223, 312–341.

BRETZ, J. H. 1928*c*. Bars of the Channeled Scabland. *Bulletin of the Geological Society of America*, **39**, 643–702.

BRETZ, J. H. 1928*d*. Bars of the Channeled Scabland (Abstract). *Bulletin of the Geological Society of America*, **39**, 159–160.

BRETZ, J. H. 1929. Valley deposits immediately east of the channeled scabland of Washington. *Journal of Geology*, **37**, 393–427, 505–541.

BRETZ, J. H. 1930*a*. Lake Missoula and the Spokane Flood. *Bulletin of the Geological Society of America*, **41**, 92–93.

BRETZ, J. H. 1930*b*. Valley deposits immediately west of the channeled scabland. *Journal of Geology*, **38**, 385–422.

BRETZ, J. H. 1932*a*. *The Grand Coulee*. American Geographical Society, Special Publications, **15**.

BRETZ, J. H. 1932*b*. *The Channeled Scabland*. 16th International Geological Congress, U. S., 1933, Guidebook **22**, Excursion C-2.

BRETZ, J. H. 1959. *Washington's Channeled Scabland*. Washington Division of Mines and Geology, Bulletin, **45**.

BRETZ, J. H. 1969. The Lake Missoula floods and the channeled scabland. *Journal of Geology*, **77**, 505–543.

BRETZ, J. H. 1980. Presentation of the Penrose Medal to J Harlen Bretz: Response. *Bulletin of the Geological Society of America, Part II*, **91**, 1095.

BRETZ, J. H., SMITH, H. T. U. & NEFF, G. E. 1956. Channeled Scabland of Washington: new data and interpretations. *Bulletin of the Geological Society of America*, **67**, 957–1049.

CALKINS, F. C. 1905. *Geology and Water Resources of a Portion of East-Central Washington*. US Geological Survey, Water-Supply Paper, **118**.

CHAMBERLIN, T. C. 1890. The method of multiple working hypotheses. *Science*, **15**, 92–96.

CONDON, T. 1902. *The Two Islands and What Came of Them*. J. K. Gill & Co., Portland, OR.

DANA, J. D. 1882. The flood of the Connecticut River valley from the melting of the Quaternary glacier. *American Journal of Science*, **23**, 87–97, 179–202, 360–373; **24**, 428–433.

DAVIS, W. M. 1926. The value of outrageous geological hypotheses. *Science*, **63**, 463–468.

DAWSON, W. L. 1898. Glacial phenomena in Okanogan County, Washington. *American Geologist*, **22**, 203–217.

FLINT, R. F. 1928. Pleistocene terraces of the lower Connecticut Valley. *Bulletin of the Geological Society of America*, **39**, 955–984.

FLINT, R. F. 1932. Deglaciation of the Connecticut Valley. *American Journal of Science*, **24**, 152–156.

FLINT, R. F. 1935. Glacial features of the southern Okanogan region. *Bulletin of the Geological Society of America*, **46**, 169–194.

FLINT, R. F. 1936. Stratified drift and deglaciation of eastern Washington. *Bulletin of the Geological Society of America*, **47**, 1849–1884.

FLINT, R. F. 1937. Pleistocene drift border in eastern Washington. *Bulletin of the Geological Society of America*, **48**, 203–231.

FLINT, R. F. 1938*a*. Origin of the Cheney–Palouse scabland tract. *Bulletin of the Geological Society of America*, **48**, 461–524.

FLINT, R. F. 1938*b*. Scabland auf dem Columbia Plateau im ostlichen Washington. *Journal of Geomorphology*, **1**, 130–139.

FLINT, R. F. 1947. *Glacial Geology and the Pleistocene Epoch*. Wiley, New York.

FLINT, R. F. 1957. *Glacial and Pleistocene Geology*. Wiley, New York.

FLINT, R. F. 1971. *Glacial and Quaternary Geology*. Wiley, New York.

GOULD, S. J. 1978. The great scablands debate. *Natural History*, **87**, 12–18.

GILBERT, G. K. 1886. The inculcation of scientific method by example. *American Journal of Science*, **31**, 284–299.

HARDING, H. T. 1929. Possible supply of water for the channeled scablands. *Science*, **69**, 188–190.

HOBBS, W. H. 1940. Glacial history of southeastern Washington. *Bulletin of the Geological Society of America*, **51**, 2024.

HOBBS, W. H. 1943. Discovery in eastern Washington of a new lobe of the Pleistocene continental glacier. *Science*, **98**, 227–230.

HOBBS, W. H. 1945. Scabland and Okanogan Lobes of the Cordilleran Glaciation, and their lake histories. *Bulletin of the Geological Society of America*, **56**, 1167.

HOBBS, W. H. 1947. *The Glacial History of the Scabland and Okanogan Lobes, Cordilleran Continental Glacier*. J. W. Edwards, Ann Arbor, MI (privately printed).

HODGE, E. T. 1934. Origin of the Washington scabland. *Northwest Science*, **8**, 4–11.

HODGE, E. T. 1940. Glacial history of southeastern Washington. *Bulletin of the Geological Society of America*, **51**, 2024.

KEYES, C. 1935. Glacial origin of the Grand Coulee. *Pan-American Geologist*, **63**, 189–202.

MALDE, H. E. 1968. *The Catastrophic Late Pleistocene Bonneville Flood in the Snake River Plain*. US Geological Survey, Professional Paper, **596**.

MCMACKEN, J. G. 1937. Vicissitudes of Spokane River in late geological times. *Pan American Geologist*, **68**, 111–132.

MEINZER, O. E. 1918. The glacial history of the Columbia River in the Big Bend Region. *Washington Academy of Science Journal*, **8**, 411–412.

O'CONNOR, J. E. 1993. *Hydrology, Hydraulics, and Geomorphology of the Bonneville Flood*. Geological Society of America, Special Paper, **274**.

OESTREICH, K. 1915. Die Grand Coulée. *In*: *American Geographical Society Memorial Volume of the Transcontinental Excursion of 1912*. American Geographical Society, Special Publications, **1**, 259–273.

PARDEE, J. T. 1910. The glacial Lake Missoula, Montana. *Journal of Geology*, **18**, 376–386.

PARDEE, J. T. 1922. Glaciation in the Cordilleran region. *Science*, **56**, 686–687.

PARDEE, J. T. 1940. Ripple marks (?) in glacial Lake Missoula, Montana. *Bulletin of the Geological Society of America*, **51**, 2028–2029.

PARDEE, J. T. 1942. Unusual currents and glacial Lake Missoula. *Bulletin of the Geological Society of America*, **53**, 1569–1600.

PARKER, S. 1838. *Journal of an Exploring Tour beyond the Rocky Mountains*. Privately published, Albany, NY.

PEIRCE, C. S. 1992. *Reasoning and the Logic of Things: The Cambridge Lectures of 1898*. Harvard University Press, Cambridge, MA.

RICHMOND, G. M., FRYXELL, R., NEFF, G. E. & WEIS, P. L. 1965. The Cordilleran Ice Sheet of the northern Rocky Mountains and related Quaternary history of the Columbia Plateau. *In*: WRIGHT, H. E. & FREY, D. G. (eds) *The Quaternary of the United States*. Princeton University Press, Princeton, NJ, 231–242.

RUSSELL, I. C. 1893. *Geologic Reconnaissance in Central Washington*. US Geological Survey, Bulletin, **108**, 1–108.

SALISBURY, R. D. 1901. Glacial work in the western mountains in 1901. *Journal of Geology*, **9**, 721–724.

SCHWENNESSEN, A. T. & MEINZER, O. E. 1918. Ground water in Quincy Valley, Washington. *US Geological Survey, Water-Supply Paper*, **425**, 131–161.

SYMONS, T. W. 1882. *Report of an Examination of the Upper Columbia River*. US Congress, Senate, 47th Congress, First Session, Senate Document, **186**.

THORNBURY, W. D. 1969. *Principles of Geomorphology*. Wiley, New York.

TRIMBLE, D. E. 1963. *Geology of Portland, Oregon and Adjacent Areas*. US Geological Survey, Bulletin, **1119**.

WAITT, R. B. 1985. The case for periodic colossal jokulhlaups from Pleistocene Glacial Lake Missoula. *Bulletin of the Geological Society of America*, **96**, 1271–1286.

WATERS, A. C. 1933. Terraces and coulees along the Columbia River near Lake Chelan, Washington. *Bulletin of the Geological Society of America*, **44**, 783–820.

WHEWELL, W. 1840. *The Philosophy of the Inductive Sciences Founded Upon Their History* (2 vols). Parker, London.