22 December 1978, Volume 202, Number 4374 SCIENCE

The Spokane Flood Controversy and the Martian Outflow Channels

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Perhaps the most significant result of the Mariner 9 and Viking missions to Mars was the realization that fluvial processes may have shaped portions of the martian surface (*1*). Persuasive evidence of flowing water on Mars is provided by current sides of flow obstacles, longitudinal grooves (indicating paleoflow streamlines), irregular "etched" zones on channel floors (locally influenced by jointing), and scour marks around obstacles (requiring turbulent flow). Although

Summary. In a series of papers published between 1923 and 1932, J Harlen Bretz described an enormous plexus of proglacial stream channels eroded into the loess and basalt of the Columbia Plateau, eastern Washington. He argued that this region, which he called the Channeled Scabland, was the product of a cataclysmic flood, which he called the Spokane flood. Considering the nature and vehemence of the opposition to his hypothesis, which was considered outrageous, its eventual scientific verification constitutes one of the most fascinating episodes in the history of modern science. The discovery of probable catastrophic flood channels on Mars has given new relevance to Bretz's insights.

a variety of troughlike features with characteristic fluvial morphologies (*2*). The largest fluvial features, termed outflow channels (*3*), display evidence of scour on a massive scale and are related to localized source regions. The water (or dynamically similar fluid) was probably released in phenomenal quantities from lithospheric sources, followed by collapse of overlying rock to form chaotic terrain (*4*).

Figure 1 is a detailed illustration of the landforms that occur in outflow channels on Mars. Some of the most important features and their genetic interpretation are the following: regional and local anastomosing patterns, expanding and contracting reaches associated with flow constrictions, streamlined uplands shaped by viscous fluid flow, inner channels with recessional headcuts, pendant forms (bars or erosional residuals) on the down-

several fluids can create morphological forms similar to one or several of these features, only the catastrophic flood hypothesis can explain the entire assemblage by a single process (*5*). The only terrestrial landscape that contains analogs to all the martian outflow features is the Channeled Scabland of eastern Washington, created by catastrophic flood flows across differentially resistant basalt, loess, and sedimentary rocks (*6*).

Despite the morphological evidence for a flood-outflow origin of channels on Mars, several investigators have continued to argue that nonfluvial processes must be found to explain the channels. Fluids other than water are sought as erosive agents because of the severe problems of maintaining liquid water on the surface of Mars under present conditions (*7*). Another criticism of the flood theory derives from skepticism concerning the efficacy of large floods for producing the indicated erosion (*8*). Various investigators have suggested the following channeling processes, which do not require water flow: tectonic factors acting alone (*9*), erosion by low-viscosity lava in turbulent flow (*10*), wind erosion (*11*), and erosion by liquid alkanes (*12*).

The continuing debate over the origin of channels on Mars has broad similarities to an earlier debate over the origin of the Channeled Scabland. Many of the same arguments have been advanced in the scientific attempt to resolve both problems. Because the full history of the scabland debates of 50 years ago has never been recounted in the published literature, I will summarize that controversy in this article.

The pronouncement by Bretz (*13*) of the catastrophic flood origin of the Channeled Scabland provides a classic example of the role of an outrageous hypothesis in scientific investigation. Olson (*14*) described the reception of the idea: "During its not always calm history, the story of the development of the Channeled Scabland was thought by some to have brushed beyond the dividing line in flaunting catastrophe too vividly in the face of the uniformity that had lent scientific dignity to interpretation of the history of the earth." The reaction of the scientific community is simply stated: "this heresy must be gently but firmly stamped out" (*15*).

An Outrageous Hypothesis

Bretz began his studies of the Channeled Scabland (Fig. 2) during the summer of 1922. His first paper on the region (actually the text of an oral presentation to the Geological Society of America) took care not to call on cataclysmic origins (*16*). However, his description of physiographic relationships in the region clearly showed that unusual geomorphic processes had been at work. An example is his description (*16*) of the preflood drainage line that was later enlarged to form the lower part of Moses Coulee:

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"The cliffs here are deeply notched by wide-open V-shaped tributary valleys. . . . These notches give the cliffs a striking resemblance to a series of great rounded gables in alignment. . . . Both widening and deepening in the basalt occurred and the tributaries were left hanging. They have since attained topographic adjustment by building large alluvial fans out on the canyon floor." He further noted that prodigious quantities of water were involved in the erosion. Referring to three outlets at the south end of the Hartline Basin (Dry Coulee, Lenore Canyon, and Long Lake Canyon), Bretz (*16*) 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."

Originally, Bretz (*16*) thought that the scabland gravel deposits were organized into terrace remnants. However, he noted that they lacked a "sharp terrace form." This interpretation was quickly modified (*13*): "the evidence seems conclusive that all gravel deposits of the scablands are bars, built in favorable situations in the great streams which eroded the channels." With this conclusion he was forced to call on catastrophic quantities of water. Since the bars were more than 30 meters in height (Fig. 3A), even greater water depths were required to form them. The second paper (*13*) also included the first detailed geomorphic map of the entire Channeled Scabland, showing the overall anastomosing pattern assumed by a great flood of water.

Bretz (*13*) was the first to recognize the streamlined loess hills of the Cheney-Palouse Scabland (Fig. 3B). He described them as follows: "A very striking and significant feature of the steepened slopes is their convergence at the northern ends of the groups to form great prows, pointing up the scabland's gradient. . . . The nose of a prow may extend as a sharp ridge from the scabland to the very summit of the hill. It is impossible to study these prow-pointed loessial hills, surrounded by the scarred and channeled basalt scablands, without seeing in them the result of a powerful eroding agent which attacked them about their bases and most effectively from the scabland's up-gradient direction." He subsequently argued that the rugged scabland of anastomosing channels and rock basins (Fig. 3C) cut into the basalt was the product of subfluvial quarrying, and described this process for the modern Columbia River near The Dalles, Oregon (*17*). Moreover, he asserted that only large vigorous streams could produce such forms.

The eventual conclusion from these varying lines of evidence was that so much glacial meltwater occupied the preexisting valleys on the Columbia Plateau that it must have constituted a vast but short-lived flood, the Spokane flood (*18*). The flood spilled across preexisting stream divides, eroding the maturely dissected loess topography to form linear channels, and leaving a legacy of

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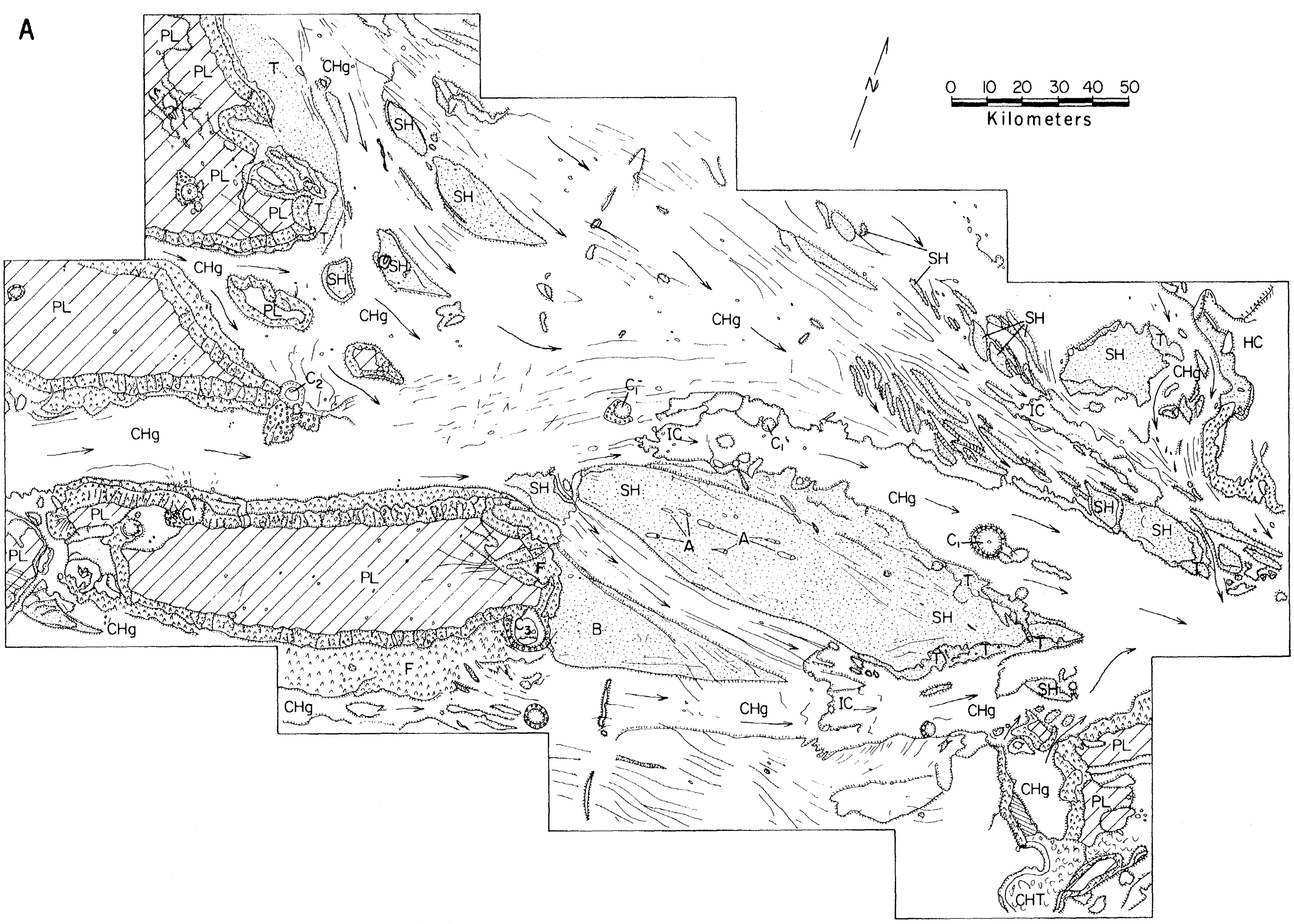

Fig. 1. (A) Detailed geomorphic map prepared from high-resolution Viking orbiter photographs of a portion of Kasei Vallis on Mars (62°W, 25°N). Features in this region indicative of catastrophic floods were first described by Baker and Milton (*2*) and include anastomosing bedrock channels (*CHg*) containing various bed forms. The erosional forms include inner channels with recessional headcuts (*IC*), longitudinal grooves, terracelike benches (*T*), and streamlined uplands (*SH*). Deposition may have occurred in areas tentatively mapped as bars (*B*). Postflood features include talus along the valley walls that merges with fans (*F*) and landslides that spread out onto the valley floors. The mapping procedure is described by Baker and Kochel (*49*).

scoured loess scarps, hanging distributary valleys, and high-level fluvial deposits. It also built the huge constructional bars of gravel, and then subsided so quickly that these bed forms were left almost unmodified by the subsiding water (*18*).

Bretz (*18*) made the first estimate of the flood discharge. He chose Wallula Gap for this calculation because of the ponding effect of the constriction. His calculated maximum flow rate was 1.9×10^6 cubic meters per second (66×10^6 cubic feet per second), but he noted that this erred toward the low side. Nevertheless, he stated that "it represents the melting of about 42 cubic miles of ice daily" (*18*). At that time the only two explanations Bretz could offer for achieving the required volumes of floodwater were (i) a very sudden climatic amelioration, and (ii) subglacial volcanism and a resulting breakout flood. Some simple calculations demonstrate the inadequacy of either explanation in producing the required volumes of water in so short a time. Nevertheless, Bretz emphasized that the lack of a known flood mechanism adequate for the task should not bring the whole catastrophic flood concept into doubt. "The writer," he said (*18*), "has repeatedly been driven to this position of doubt, only to be forced by reconsideration of the field evidence to use again the conception of enormous volume. . . . These remarkable records of running water on the Columbia Plateau and in the valleys of Snake and Columbia rivers cannot be interpreted in terms of ordinary river action and ordinary valley development. . . . Enormous volume, existing for a very short time, alone will account for their existence."

The Spokane Flood Debate

In 1927 the Geological Society of Washington invited Bretz to give a lecture on "Channeled Scabland and the Spokane Flood." It was a purposeful invitation: a veritable phalanx of doubters had been assembled to debate the flood hypothesis. Bretz (*19*) presented the bas-

B

	Description	Interpretation
PL	Plateau material as typical of the Lunae Planum.	Milton (1974) interpreted the Lunae Planum materials as possible basaltic lava flows underlain by less consolidated material, perhaps sediments.
CHg	Channels and inferred flow direction.	Approximate direction of catastrophic flood flow across this surface.
	Dark-appearing lineations that parallel the inferred flow directions.	Longitudinal grooves eroded parallel to flood flow by large roller vortices (macroturbulence).
IC	Inner channel headcuts.	Headwardly-eroding inner channel cataracts developed during flooding.
SH	Streamlined hills and uplands. Prows point upstream, and downstream ends have tapering tails.	Erosional remnants, often downstream from flow obstructions, whose streamlined shape results from high velocity fluvial activity.
T	Terrace-like benches along edges of streamlined hills and plateaus.	Lithologic units of varying resistance to plucking erosion that have been differentially stripped by catastrophic flood flows.
B	Bars?	Possible accumulation of flood debris downstream from flow obstructions.
	Talus accumulations.	Blocky talus piles resulting from back wasting.
F	Fans, often possessing radiating flow lines and a lobate front.	Portions of the talus slopes that have flowed across adjacent channel floor.
	Slumps.	Rotational landslides.
CHT	Chaotic terrain.	Result from collapse over melted ground ice.
A	Light-appearing zones developed behind craters.	Eolian deposits.
	Lineations oblique to inferred flow direction.	Joints, faults, and other bedrock structures accentuated by erosion.
C_1	Craters with raised rims that have not interacted with channeling processes.	Relatively young craters that have not been modified by catastrophic flood flows.
C_2	Crater with poorly preserved rim morphology.	Crater rim is highly degraded and partly buried but not modified by catastrophic flood processes.
C_3	Exhumed craters.	Craters from a buried landscape that were exhumed by catastrophic flood flows.
	Crater rims and hummocky zones with lobate raised margins.	Crater ejecta, partially deposited by fluid debris flows released when meteors impacted the cryolithosphere.

All the mapped craters are C_1 unless otherwise noted.

Fig. 1. (B) Legend for the geomorphic map.

Table 1. Outline of some significant geomorphic features in the Channeled Scabland and adjacent areas (19, 24).

Channel morphology
Scale: valleys are really the channels that conveyed huge flood flows
Rock basins: lengths up to 14 km, depths up to 60 m
Plexus grouping of channels
Cataracts: several more than 5 km wide and 120 m high
Interchannel areas: loess
Aligned loess scarps facing the channels: slopes eroded to 30° to 35°
Streamlined residual loess hills
Divides: deeply trenched by multiple channels at approximately equal elevation (that of the flood high-water surface)
Depositional features
Gravel, commonly containing boulders several meters in diameter
High gravels up to 120 m above canyon floors contemporaneous with floor deposits
Bar morphology: bars up to 30 m high
Great fan deposit in northern Quincy Basin
Regional anastomosis: results from the abrupt introduction of a huge volume of water flooding a multitude of minor valleys and crossing a multitude of minor preflood divides
Wallula Gap scabland: shows ponding of floodwater by hydraulic damming at a narrow constriction
Downstream continuity of flood features
Flood bars along Columbia Gorge through Cascade Mountains, downstream from Wallula Gap
Huge fan delta developed at Portland, Oregon

ic outline of his theory to date, citing the detailed field evidence that he could not explain by any hypothesis other than a great flood of water (Table 1). The first discussant was Alden (20), who cautiously warned of the difficulties with the hypothesis. Lacking personal field experience in the region, he suggested that the rock basins might be collapsed lava caves, but he realized that the major features indicated stream erosion. "It seems to me impossible that such part of the great ice fields as would have drained across the Columbia Plateau could, under any probable conditions, have yielded so much water as is called for in so short a time. . . . It appears that ice sheets of three distinct stages of glaciation invaded the borders of this region and may have afforded conditions of repeated floodings of much smaller volume" (20).

Meinzer (21) voiced the commonly held view of the channeled scabland: "the Columbia River, is a very large stream, especially in its flood stages, and it was doubtless still larger in the Pleistocene epoch. Its erosive work in the Grand Coulee . . . appears to me about what would be expected from a stream of such size when diverted from its valley and poured for a long time over a surface of considerable relief that was wholly unadjusted to it." He argued that the glacially swollen Columbia could easily have cut the dry falls and deposited the great gravel fan of the northern Quincy Basin. He described the Quincy Basin as containing an extensive series of terraces, explained by progressive abandonment as the glacial Columbia cut down to lower levels (22).

McKnight (23), who was also a participant in the Washington discussions, suggested that a glacially diverted Columbia River was a viable alternative to Bretz's hypothesis. In response, Bretz (24) argued that the great flood channels and bars near Gable Mountain (in the Pasco Basin) were far too large to be ascribed to the Columbia River. He made his position quite clear: "I think I am as eager as anyone to find an explanation for the channeled scabland of the Columbia Plateau which will fit all the facts and will satisfy geologists. I have put forth the flood hypothesis only after much hesitation and only when accumulating data seemed to offer no alternative."

Another of those at the Washington meeting who was upset with Bretz's hypothesis was Gilluly (25). Although he had not studied the Channeled Scabland in the field, he presented an imaginative and persuasive argument for the creation of the unusual landforms by the long-continued erosion of present-sized streams. He took exception to a minor point concerning the use of talus heights as time indicators and then attacked the major weak point in the flood hypothesis, the problem of the flood's source. He concluded, in essence, that Ockham's razor did not apply to the Channeled Scabland and called for a more complex sequence of adjustments by floods or rivers not much larger than the Columbia (26). In reply, Bretz (19) asked whether the lack of a documented source for the flood was proof that the flood did not exist. He argued that the scabland phenomena themselves required the existence of a great flood.

Among the spectators at the Washington lecture was J. T. Pardee of the U.S. Geological Survey. Several years earlier he had been sent to study the Channeled Scabland by W. C. Alden, chief of Pleistocene geology at the Survey. In a brief report (27), he proposed that the Cheney-Palouse scabland tract had been created by glaciation of a rather unusual character. Bretz later visited Pardee's field locations and found that his "glacial" deposits were flood bars (28). The correspondence in the mid-1920's between Alden, Bretz, and Pardee suggests that Pardee was really considering a hypothesis that the scablands might be related to drainage from a large Pleistocene lake that he had studied in the western part of Montana (29). It appears that Alden dissuaded him from that idea (30). Apparently Pardee knew the source of the great scabland floods even as Bretz was struggling to defend his hypothesis to doubters at the Washington meeting.

Bretz finally solved the problem of the source of the Spokane flood in 1928. Although Harding (31) made the first announcement of Bretz's idea, Bretz (32) later published the hypothesis that scabland flooding could have resulted from an abrupt failure of the ice dam that retained Glacial Lake Missoula (29). Bretz (33) clearly illustrated the relationship of Lake Missoula to the Channeled Scabland (Fig. 4).

For the next several years after the Washington meeting, Bretz continued to answer various criticisms of his flood hypothesis (34, 35), and he established some new lines of inquiry into the problem. He showed that each of the valleys entering the eastern margin of the scabland spillways contained flood deposits emplaced by phenomenally deep water flowing *up* the tributaries away from the scabland channels (36). He traced these deposits along the Snake River to beyond Lewiston, Idaho, more than 140 kilometers upstream from the nearest scabland channel. The conclusion again defied conventional wisdom (36): "Up-valley currents of great depth and great 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." Each subsequent study produced yet another affirmation of the flood theory. In 1930 Bretz (37) wrote, "The writer, at least normally sensitive to adverse criticism, has no desire to invite attention simply by advocating extremely novel views. Back of the repeated assertion of the verity of the Spokane Flood lies an unique assemblage of erosional forms and glacial water deposits; an assemblage which can be resolved into a genetic scheme only if time be very short, volume very large, velocity very high, and erosion chiefly by plucking of the jointed basalt."

The published record of the Spokane flood debate is clear on one major point. Bretz repeatedly asked only that his flood hypothesis be considered, not by emotion or intuition, but by the established principles of the scientific method. His detailed paper on the scabland bars contains the most eloquent expression of this plea (*38*):

> 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 can not be placed there unless errors of observation and direct inference are demonstrated. The writer insists that until then it should not be judged by the principles applicable to valley formation, for the scabland phenomena are the product of river channel mechanics. If this is in error, inherent disharmonies should establish the fact, and without adequate acquaintance with the region, this is the logical field for critics.

The Revisionists

By the early 1930's the Channeled Scabland problem had become something of a sensation for American geology. Bretz had published the last of his field results (*33, 39*) and had embarked on new problems. His monumental but controversial field study was now open to the kind of attack that he himself had so strongly urged—new field studies.

Allison (*40, 41*) was the first to enter the foray. His view was not a denial of the Spokane flood, but a modification. He argued that it was floating ice, rather than mere water volume, that was the critical factor in the flood. He presented detailed evidence for the ponding of floodwater all the way from the Columbia River gorge upstream to the Wallula Gap. This ponding was produced ("in spite of the obvious difficulties of such an explanation") by an immense ice jam in the Columbia gorge. The blockade supposedly grew gradually headward until it extended into eastern Washington. As water was dammed to higher levels it spilled across secondary drainage divides, creating the enigmatic hanging valleys, high-level gravels, and widely distributed erratics. In his last sentence Allison said, "perhaps this revision will make the idea of such a flood more generally acceptable" (*40*).

The most serious alternative to the Spokane flood hypothesis was that posed by Flint (*42*). In many ways Flint's study

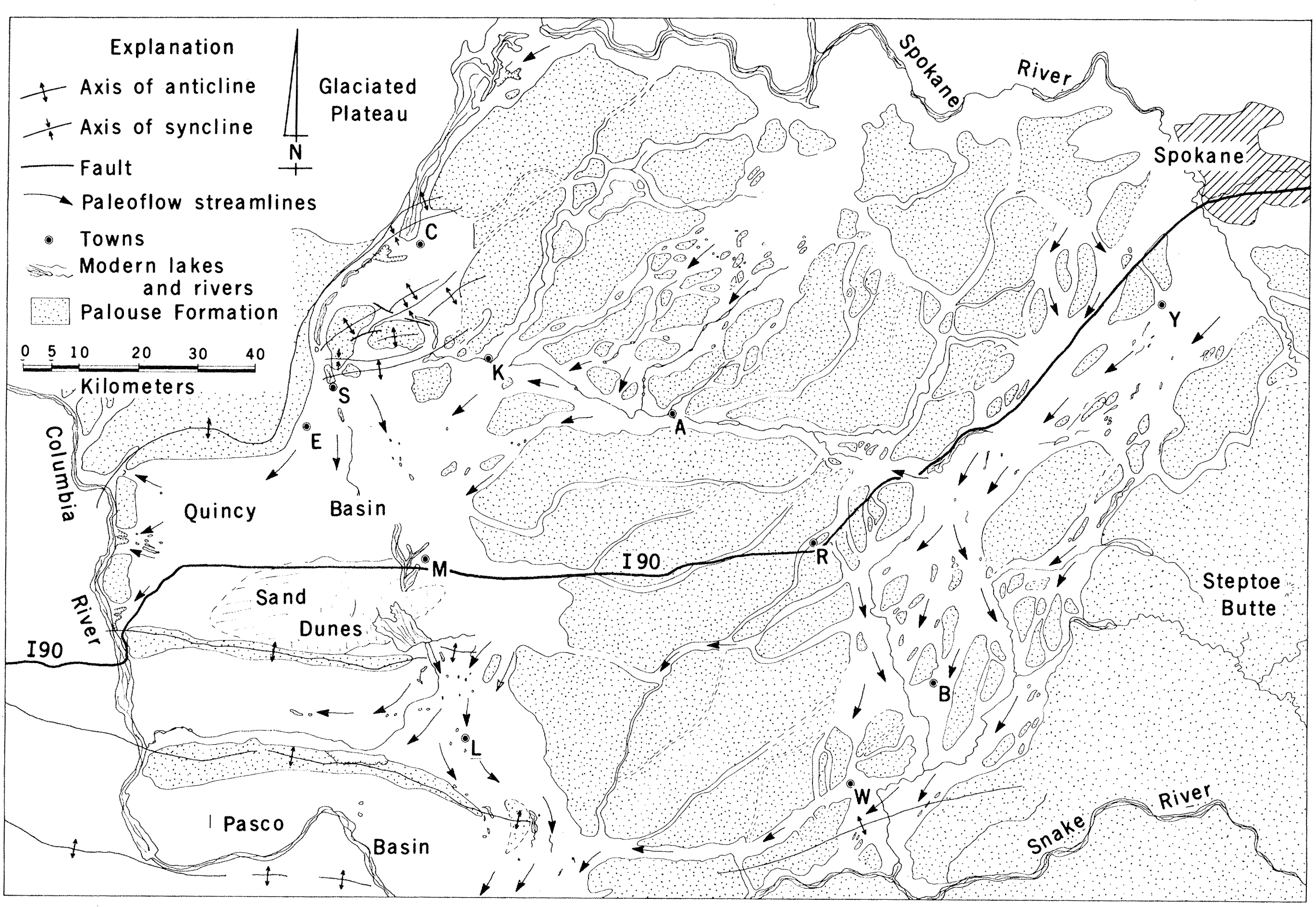

Fig. 2. Regional pattern of the Channeled Scabland in eastern Washington as mapped from orbital photographs (Landsat images E-1039-18145-5 and E-1004-18201-7). The anastomosing pattern of the great flood channels is approximated by the boundaries of loess (Palouse Formation) mantling divide areas that were not scoured by flooding. Features and locations mentioned in this article include the Grand Coulee [extending north from Coulee City (*C*)], the Hartline Basin (just south of Coulee City), the Crab Creek scabland tract [extending through Odessa (*A*), and Wilson Creek, (*K*)], the Palouse-Snake divide crossing [south of Washtucna (*W*)], and the Cheney-Palouse scabland tract [extending from Cheney (*Y*) through Benge (*B*) to Washtucna]. Other locations are Moses Lake (*M*), Ephrata (*E*), and Soap Lake (*S*). A more complete discussion of the region is given by Baker and Nummedal (*50*).

is one of the most ironic in the annals of geology. He presented a carefully worded argument that cited a considerable amount of field data. He stated that the scabland gravel was relatively fine-grained: "Gravel coarser than pebble size is common only in the northern part of the tract" (42). This description was combined with the observation of relatively good size sorting and fair to good rounding to suggest "a picture of leisurely streams with normal discharge." It is obvious from Flint's sedimentological descriptions that he was giving most of his attention to the slack-water facies of the Missoula flood deposits in the various scabland channels.

One of Flint's most important arguments was that the surface form of the scabland deposits was that of "nonpaired, stream-cut terraces in various states of dissection." It was an idea that Bretz had introduced (16) and subsequently rejected after closer field study. Flint thought that Bretz's revised interpretation of the deposits as constructional bar forms could explain some but not all of the field relationships. He suggested that a sequence of channel aggradation by normal proglacial outwash was followed by dissection to leave remnants of fill that occasionally resembled bar forms.

Flint (42) accepted Bretz's arguments (38) that the flood gravel often (i) occurred in the lee of islandlike hills, (ii) had rounded upper surfaces, and (iii) exhibited a parallelism of surface slopes with the dip of underlying foresets. He argued that "terraces" had been extensively dissected by a downstream base-level reduction. The terraces were preferentially preserved in the lee of islandlike hills. In addition, the low precipitation plus the high permeability of the gravel prevented gullying, so the gravel deposits developed rounded slopes by dry creep. Finally, he showed that many of the gravel slopes did indeed truncate the underlying bedding. As specific cases, he argued that Bretz's Willow Creek bar, Staircase Rapids bar, Palouse Canyon bar, Midcanyon bar, and Shoulder bar were all simply terrace remnants.

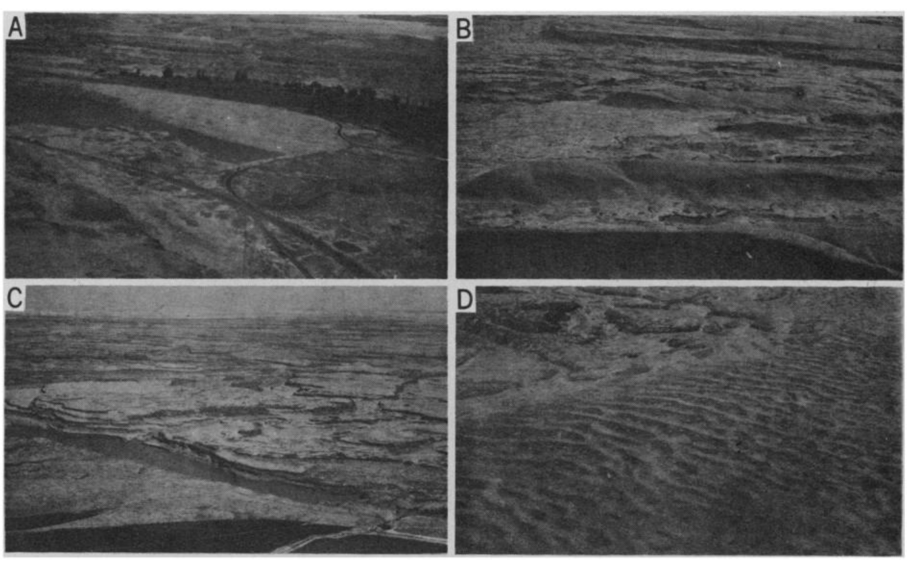

Fig. 3. Features indicative of catastrophic flooding in the Channeled Scabland. (A) Bar of flood gravel in the upper Crab Creek scabland tract. This bar is relatively small by scabland standards, 1 km long and 25 m high. It is elongated in the paleoflow stream direction downstream from a resistant ledge of basalt in the lower right foreground. The basalt ledge probably induced flow separation in the floodwater, which was approximately 120 m deep in this area (51). The separation zone then accumulated boulders and gravel that otherwise would have been transported along by the high-velocity floodwater. (B) Streamlined loess on the former Palouse-Snake drainage divide, which was crossed by catastrophic flood flows. Slopes on the upstream margins of these hills converge to form definite prows that point up the local scabland gradient. The easily scoured loess comprising these hills was preserved in the flood because the hills developed shapes of minimum resistance to flow. Baker (53) notes that these hills are equilibrium forms, elongated sufficiently to reduce pressure drag, but not so long that they created excessive skin resistance. The streamlining involved elongation to about three times the maximum width presented transverse to the flow by the hill. (C) Typical butte-and-basin scabland at Drumheller Channels 15 km southeast of Moses Lake. This type of erosion results from macroturbulent plucking of jointed basalt by extremely deep, high-velocity water (52). (D) Giant current ripples on the great flood bar at Marlin, Washington, in the upper Crab Creek scabland tract. These ripples average 60 m in spacing and 2 m in height. They developed in a region where floodwater was 60 m deep and flowing with a mean velocity of approximately 12 m/sec (51). Larger ripples are associated with flows that were deeper or faster, or both. The giant ripples are composed of gravel and boulders up to 1.5 m in diameter. Nearly 100 sets of giant current ripples are recognized throughout the Channeled Scabland.

Flint confined his discussion to the eastern portion of the Channeled Scabland, called the Cheney-Palouse tract. Erosion was less spectacular there than elsewhere in the Channeled Scabland, and he attributed it to proglacial meltwater streams whose discharge "was less than that of the Snake River today" (42). The streams, he believed, had emptied into a lake. As this lake rose, the leisurely streams that Flint envisioned aggraded, forming a thick fill. This fill blocked preglacial tributaries to the Channeled Scabland, such as the Snake River, and formed marginal lakes that accumulated fine-grained sediments. The steep scarps on the Palouse loess were then cut by lateral planation of the streams flowing on this fill. When the lake finally drained, the streams gradually incised the fill to form terraces. Moreover, Flint was able to explain the enigmatic notched spurs and slotlike hanging canyons as the result of superposition of streams from his widespread fill rather than of divide crossing by catastrophic floodwater.

A careful examination of Flint's paper reveals that he observed and described the morphological feature that, more than any other, was incompatible with his elegant theory. On the surfaces of the scabland terraces he described an intricate microtopography of anastomosing channels, small depressions, and crescentic channels (42). In other areas he observed "mammillary undulatory topography." As an example he gave the precise location of the train of giant current ripples on the upper surface of Staircase Rapids bar, 3 km north of Washtucna. Although another set of ripples that he described are somewhat masked by overlying slackwater sediments, Flint even stated the characteristic ripple magnitude: "The undulations are 20 to 100 feet long, and have amplitudes up to 10 feet. Their axes are generally transverse to the Snake River." It is ironic that Flint was the first to accurately describe the very features that Bretz *et al.* (15) later presented as incontrovertible evidence for catastrophic flood flows.

Vindication

By 1940 several other geologists were also at work attempting to disprove Bretz (43). The stage was set for a dramatic revelation from an unexpected source. The occasion was a meeting of the American Association for the Advancement of Science in Seattle. Flint presented his hypothesis, but Bretz refused the invitation to confront him, stating that the field evidence spoke for itself. Indeed it did. No one present at the session could have anticipated what J. T. Pardee would say when he rose to speak on "Ripple Marks (?) in Glacial Lake Missoula." He quietly described these ripple marks as 15 m high and 150 m in spacing.

Pardee's written paper (*44*) also had an understated title: "Unusual Currents in Lake Missoula." His work, which began before Bretz's studies, clearly demonstrated that Lake Missoula was the source of catastrophic floods through the Channeled Scabland. He noted that about 2000 km^3 of water was impounded behind a glacial lobe that occupied the basin of modern Pend Oreille Lake in northern Idaho. Pardee believed that this glacial dam had failed suddenly, with a resultant rapid draining of the lake. Evidence for this failure included severely scoured constrictions in the lake basin, huge bars of current-transported debris, and the giant current ripple marks (*45*).

In 1952 Bretz, then nearly 70 years old, returned for his last summer of fieldwork in the Channeled Scabland. The purpose was to investigate new data that had been obtained in surveys for the Bureau of Reclamation's Columbia Basin project. He was accompanied by H. T. U. Smith, who was to act in the field as "skeptic for all identifications and interpretations" (*15*), and G. E. Neff of the Bureau of Reclamation. That study (*15*) answered with meticulous detail all previous criticisms of the flood hypothesis.

Central to the new investigation was the study of the scabland depositional features. Extensive excavations for the irrigation project and new topographic maps proved that the gravel hills called bars by Bretz (*38*) were indeed subfluvial depositional bed forms. Most convincing of all was the presence of giant current ripples on the upper bar surfaces (Fig. 3D). These showed clearly that bars 30 m high were completely inundated by flows of water. Numerous giant current ripples were found on the bars that Flint had interpreted as terraces. Such features could only have been produced by the flow velocities associated with truly catastrophic discharges. Bretz's earlier interpretations were modified to allow for several episodes of flooding (*15, 46*). The central result of their study, however, was that only a hypothesis involving flooding could account for all the features of the Channeled Scabland (*47*).

The Value of Outrageous Hypotheses

When Bretz published his work on the Channeled Scabland, the paradigm of geology was uniformity. The Spokane flood hypothesis appeared to contradict the uniformitarian tradition that made geology a science in the 19th century. Indeed, it was not until after 1840 that the flood theory fell into serious decline. The catastrophist idea of the Noachian debacle was finally laid to rest when Louis Agassiz showed that his glacial theory could explain erratics, striations, till, fluvioglacial features, and so on. Old ideas die hard, however, and catastrophist absurdities still appeared in the literature of the early 1900's (as they do even today). Little wonder then that Bretz's Spokane flood hypothesis appeared as anathema to many of his contemporaries.

Simultaneously, the Spokane flood hypothesis established a conflict between two cornerstones of geological philosophy: (i) the triumph of the glacial theory over diluvial myth and (ii) the scientific tolerance of outrageous hypotheses. It is a classic dilemma for the scientist to distinguish absurdity from outrage. A foolish idea is self-evident, but the rare, creative insight that passes all reasonable bounds in the consensus of knowledge is not. The following remarks were made by a former president of the Geological Society of America: "How narrowly limited is the special field, either in subject or locality, upon which a member of the Geological Society of America now ventures to address his colleagues. . . . I wonder sometimes if younger men do not find our meeting rather demure, not to say a trifle dull; and whether they would not enjoy a return to the livelier manners of earlier times. . . . [Their] feeling of discouragement must often be shared by the chairman of a meeting when, after his encouraging invitation, 'This interesting paper is now open for discussion,' only silence follows. . . . We shall be indeed 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 accepted principles."

After speaking these words in 1925, Davis (*48*) made the case for the value of

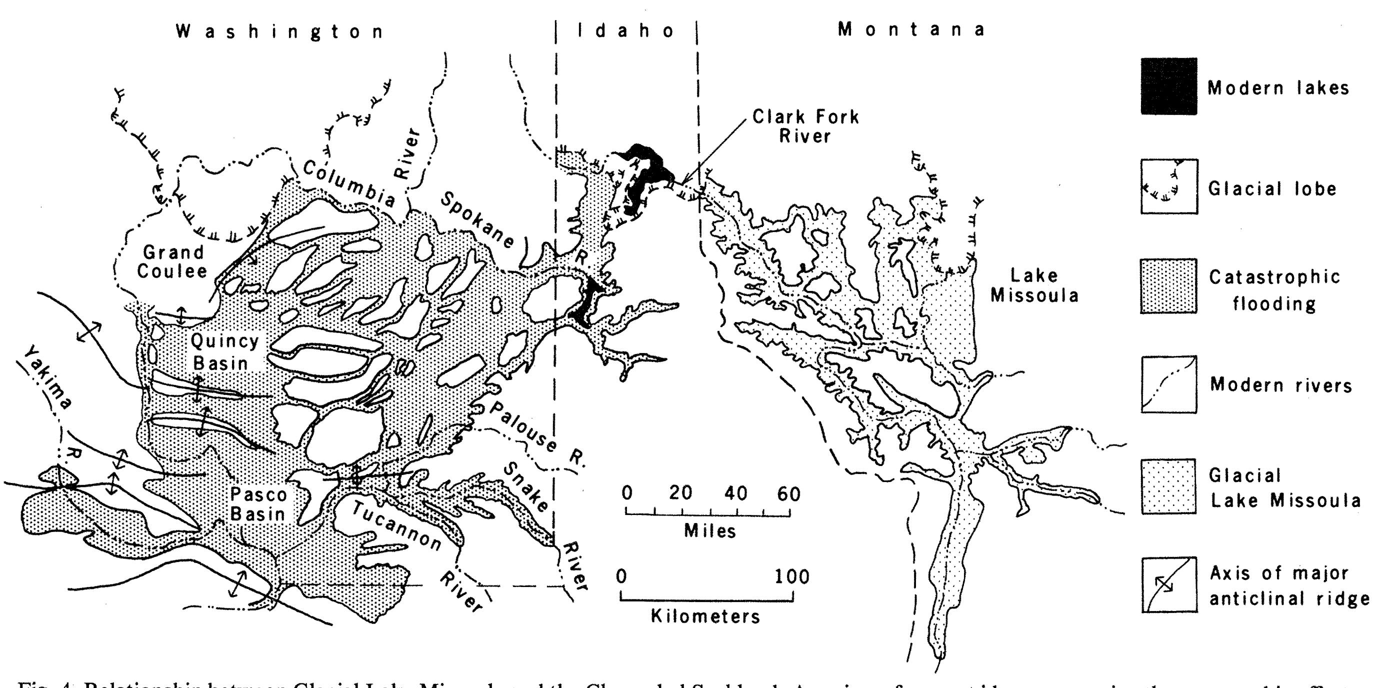

Fig. 4. Relationship between Glacial Lake Missoula and the Channeled Scabland. A review of current ideas concerning the geomorphic effects of Lake Missoula flooding is given by Baker and Nummedal (*50*).

outrageous geological hypotheses, even suggesting that geologists seriously consider "the Wegener outrage of wandering continents." He concluded by saying that the valuable outrage was that which encouraged the contemplation of other possible behaviors—not, he stated, "merely a brief contemplation followed by an off-hand verdict of 'impossible' or 'absurd,' " but a "contemplation deliberate enough to seek out just what conditions would make the outrage seem permissible and reasonable."

The Spokane flood controversy is both a story of ironies and a marvelous exposition of the scientific method. One cannot but be amazed at the efforts made to give a uniformitarian explanation for the Channeled Scabland and to uphold the framework of geology as it had been established in the writings of Hutton, Lyell, and Agassiz. The final irony may be that Bretz's critics did not appreciate the scientific implications of Agassiz's famous dictum, "study nature, not books." Perhaps no geologist has understood and lived the spirit of those words more enthusiastically than J Harlen Bretz.

References and Notes

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4. Suggestions for the origin of the outburst flooding include the liquefaction of large volumes of loosely consolidated materials beneath more competent materials, which subsequently collapsed to form the chaotic terrain [J. F. McCauley, M. H. Carr, J. A. Cutts, W. K. Hartmann, H. Masursky, D. J. Milton, R. P. Sharp, D. E. Wilhelms, *Icarus* **17**, 298 (1972); D. Nummedal, *NASA Tech. Memo. 79729* (1978), p. 257], rapid dissociation of clathrate compounds in the martian permafrost [D. J. Milton, *Science* **183**, 654 (1974)], volcanic melting of permafrost [H. Masursky, J. M. Boyce, A. L. Dial, G. G. Schaber, M. E. Strobell, *J. Geophys. Res.* **82**, 4016 (1977)], and bursts of water from aquifers confined by the martian permafrost [M. H. Carr, *NASA Tech. Memo. 79729* (1978), p. 260].
5. V. R. Baker, *Geol. Soc. Am. Abstr. Programs* **9**, 887 (1977); in *Lunar and Planetary Science IX* (Lunar and Planetary Institute, Houston, 1978), p. 38.
6. The catastrophic floods that caused the Channeled Scabland during the late Pleistocene are the largest that can be documented in the terrestrial geologic record. My paleohydraulic reconstruction (*51, 52*) indicates that discharges were as great as 21.3×10^6 m³/sec. Maximum flow velocities as high as 30 m/sec were achieved because of a unique combination of great flow depths (> 100 m) and steep water-surface gradients (> 10 m/km). A complex suite of scabland bed forms is hydraulically scaled to these phenomenal flow parameters (*53*).
7. R. B. Leighton and B. C. Murray, *Science* **153**, 136 (1966). However, calculations by R. E. Lingenfelter, S. J. Peale, and G. Schubert [*ibid.* **161**, 266 (1968)] and by D. Wallace and C. Sagan (in preparation) demonstrate that water flows can be sustained under present martian conditions because ice forming on the surface of a stream will effectively insulate the underlying liquid water flow.
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14. E. C. Olson, *ibid.* **77**, 503 (1969).
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16. J H. Bretz, *ibid.* **34**, 573 (1923).
17. ——, *J. Geol.* **32**, 139 (1924).
18. ——, *ibid.* **33**, 97 (1925).
19. ——, *J. Wash. Acad. Sci.* **17**, 200 (1927).
20. W. C. Alden, *ibid.*, p. 203.
21. O. E. Meinzer, *ibid.*, p. 207.
22. A difficulty with this idea that Meinzer appreciated from his own fieldwork in the Quincy Basin (*54*) was that four great spillways led out of the region where water had obviously been ponded. Bretz (*13*) had shown that the upper limits of the torrents that poured through these spillways occurred at the same altitudes. Rather than ascribing this coincidence to contemporaneous operation, Meinzer (*21*) actually published the idea that the spillways had been cut one at a time, and subsequent minor earth movements had later brought them to an equivalent altitude. "This recent deformation may account to some extent for channels cut through ridges that can not otherwise be well explained except by assuming excessive depths of flood water."
23. E. T. McKnight, *J. Geol.* **35**, 453 (1927).
24. J H. Bretz, *ibid.*, p. 461.
25. J. Gilluly, *J. Wash. Acad. Sci.* **17**, 203 (1927).
26. Bretz (*56*) cited correspondence from Aaron Waters relating that Gilluly subsequently changed his mind in this matter. Many years after the incident at the Washington Academy of Science, Gilluly visited the Channeled Scabland on a field excursion. As he observed Palouse-Snake divide crossing, a major scabland stream channel, his astonishment changed to a smiling comment, "How could *anyone* have been so wrong?" Nevertheless, the emotion of those days is evinced by the many eminent geologists who continued to deny the flood hypothesis and apparently never changed their minds on the matter: W. C. Alden, K. Bryan, W. H. Hobbs, F. Leverett, G. R. Mansfield, J. C. Merriam, O. E. Meinzer, and G. O. Smith.
27. J. T. Pardee, *Science* **56**, 686 (1922).
28. J H. Bretz, personal communication (1978).
29. J. T. Pardee, *J. Geol.* **18**, 376 (1910).
30. Bretz (*55*) recounted Alden's memorandum of 25 September 1922 to David White, chief geologist of the U.S. Geological Survey, in which Alden said of Pardee's work, "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." White later asked Bretz if he knew what W. C. Alden's middle name was (*55*). When Bretz replied in the negative, White said, "It's Cautious, Bretz, Cautious."
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34. ——, *J. Geol.* **36**, 193 (1928).
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36. ——, *J. Geol.* **37**, 393 (1929).
37. ——, *ibid.* **38**, 385 (1930).
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39. ——, "The Channeled Scabland," *16th Int. Geol. Congr. Guideb. 22, Excursion C-2* (1932), pp. 1–16.
40. I. S. Allison, *Geol. Soc. Am. Bull.* **44**, 675 (1933).
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42. R. F. Flint, *Geol. Soc. Am. Bull.* **49**, 461 (1938).
43. Glacial origins for the scabland features were advanced by several investigators. Hodge (*57*) hypothesized a complex alternation of ice advances and drainage changes that were never adequately documented with field evidence. Keyes (*58*) suggested that the enormous scabland coulees were simply proglacial meltwater drainage features that developed during ice-sheet retreat. Again, lack of field evidence for the idea was its major shortcoming. Hobbs (*59*), an eminent glacial geologist from the University of Michigan, developed an idea that the Channeled Scabland was produced by glacial scour at the same time that the Palouse loess was being deposited by winds blowing off ice that occupied various channels. In an extensive manuscript he described scabland gravel deposits (Bretz's "bars") as moraine remnants modified by glacier-border drainage. The paper was reviewed for the Geological Society of America by Bretz and Flint, both of whom recommended rejection. After a subsequent rejection by the American Philosophical Society (Bretz again reviewed), he published the paper privately and distributed it to most of the prominent geologists of the time (*60*).
44. J. T. Pardee, *Geol. Soc. Am. Bull.* **53**, 1569 (1942).
45. Neither in his talk nor in the resulting paper (*44*) did Pardee state the connection of Lake Missoula to the Channeled Scabland, perhaps leaving that point generously to Bretz. Even Alden remained cautious to the end. In his last published report on Lake Missoula (*61*) he observed: "Abrupt release of water from lowering of the ice dam . . . *might* result in floods of great magnitude. . . . Each may, *perhaps*, have been the origin of many violent floods that are *supposed* to have swept over the scabland" (emphasis added).
46. J H. Bretz, *Wash. Div. Mines Geol. Bull. 45* (1959), pp. 1–57.
47. The end of the Spokane flood controversy probably came during a geological excursion, Field Conference E of the 7th Congress of the International Association for Quaternary Research. In August 1965 an international party of geologists observed the evidence in Montana for Lake Missoula's catastrophic outbursts. They then traveled through the Channeled Scabland, studying the giant current ripples, flood gravel bars, and scabland erosion forms. Bretz was unable to participate in the trip because of ill health. When the field party had finished viewing the region, they sent him a long telegram that opened with "greetings and salutations" and closed with the sentence, "We are now all catastrophists" (*62*).
48. W. M. Davis, *Science* **63**, 463 (1926).
49. V. R. Baker and R. C. Kochel, in *Lunar and Planetary Science IX* (Lunar and Planetary Institute, Houston, 1978), p. 35.
50. V. R. Baker and D. Nummedal, *The Channeled Scabland* (NASA Office of Space Science, Planetary Geology Program, Washington, D.C., 1978).
51. V. R. Baker, *Geol. Soc. Am. Spec. Pap. 144* (1973).
52. ——, in *The Channeled Scabland*, V. R. Baker and D. Nummedal, Eds. (NASA Office of Space Science, Planetary Geology Program, Washington, D.C., 1978), pp. 59–79.
53. ——, in *ibid.*, pp. 81–115.
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61. W. C. Alden, *U.S. Geol. Surv. Prof. Pap. 231* (1953).
62. J H. Bretz, *J. Geol.* **77**, 505 (1969).

63. I thank J Harlen Bretz for sharing his personal recollections of the incidents described in this article and for providing unfailing inspiration and encouragement for my own studies of the Channeled Scabland. Work on this article was supported by the Planetary Geology Program, Office of Space Science, National Aeronautics and Space Administration, under grants NGR 44-012194 and NSG-7326. Additional support was provided by the Geology Foundation, University of Texas, Austin.