The Channeled Scabland: A Retrospective

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Key Words

catastrophism, floods, fluvial erosion, megaflooding, uniformitarianism

Abstract

The Channeled Scabland of east-central Washington in the United States is a complex of anastomosing rock-cut fluvial channels, cataracts, loess islands, rock basins, broad gravel deposits, and immense gravel bars. In the 1920s, J Harlen Bretz demonstrated that the Channeled Scabland formed by cataclysmic erosion and deposition from Pleistocene megaflooding derived from the margins of the Cordilleran Ice Sheet, particularly glacial Lake Missoula in western Montana and northern Idaho. Studies of this region and the high-energy flood processes that generated it are stimulating (*a*) discoveries of similar megaflood-related landscapes around the world and on Mars, (*b*) enhanced understanding of the processes involved in the fluvial erosion of bedrock, and (*c*) the use of paleoflood indicators for understanding the magnitudes and frequency of flooding.

INTRODUCTION

Scabland: scoured rock surfaces (generally basalt) typically characterized by small buttes, basins, potholes, and irregular troughs

Anastomosing: fluvial pattern that develops by channel branching and reuniting around areas of remnant bedrock or floodplain

The Channeled Scabland region is that portion of the basaltic Columbia Plateau and Columbia Basin in east-central Washington state that was shaped by Pleistocene megaflooding (**Figure 1**) into a spectacular complex of anastomosing channels, cataracts, loess islands, rock basins, broad gravel deposits, and immense gravel bars. By explaining this assemblage as the result of erosion and deposition by cataclysmic flooding, J Harlen Bretz (J is the entire first name, not an abbreviation to be followed by a period) initiated one of the great scholarly debates in the history of the Earth sciences (Baker 1978a, 1981, 1995, 2008a). Bretz was led to his "outrageous hypothesis" by detailed study of the field relationships, most notably multiple levels of divide crossings, cataracts, gravel bars, and rock basins. He concluded that so much floodwater crossed the plateau that it completely filled the preexisting valleys, thereby allowing water to spill across the intervening divides. In this way, the preflood valleys were transformed to a complex of dividing and rejoining channel ways, which Bretz (1923a,b) named the Channeled Scabland.

The Channeled Scabland is developed on a gently warped plateau-like surface of predominantly basalt bedrock, the northern and western margins of which are marked by an arc of the Columbia River (**Figure 2**). Though commonly known as the Columbia Plateau, this region is structurally a large basin that was downwarped to near sea level in the southwest at Pasco, Washington, after the Miocene emplacement of the bulk of the basalt. The surface rises northeastward to elevations of 1000 m, and knobs of older crystalline rock, such as Steptoe Butte, locally protrude through the basalt. A series of generally east-west ridges, with relief of up to 600 m, mark the crests of anticlines (**Figure 2**) in the southwestern portion of the region. These have prominent water gaps and breaches that constricted the cataclysmic flood flows.

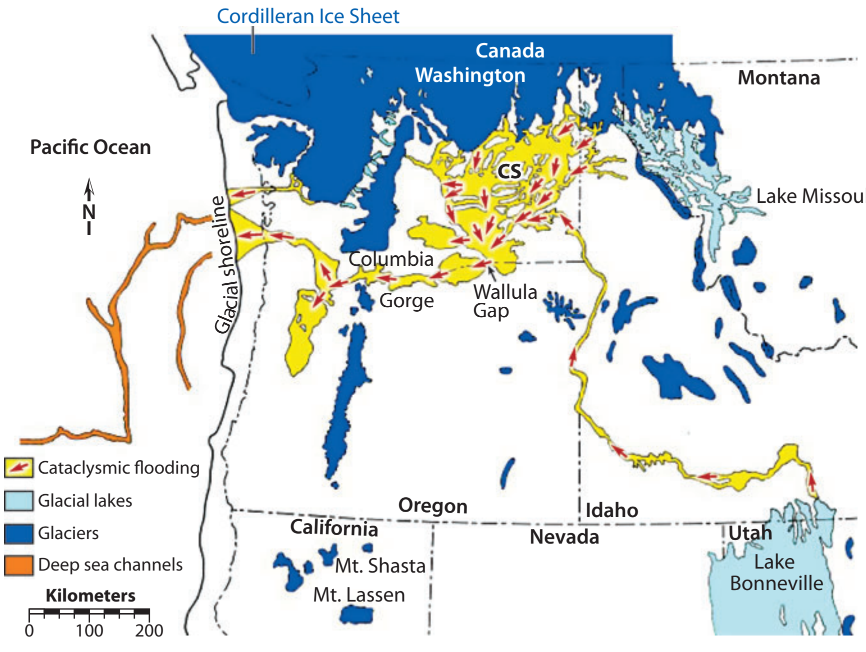

Figure 1

Regions of the northwestern United States affected by late Pleistocene cataclysmic flooding. The Channeled Scabland (CS) is located immediately south of the Cordilleran Ice Sheet and west of glacial Lake Missoula.

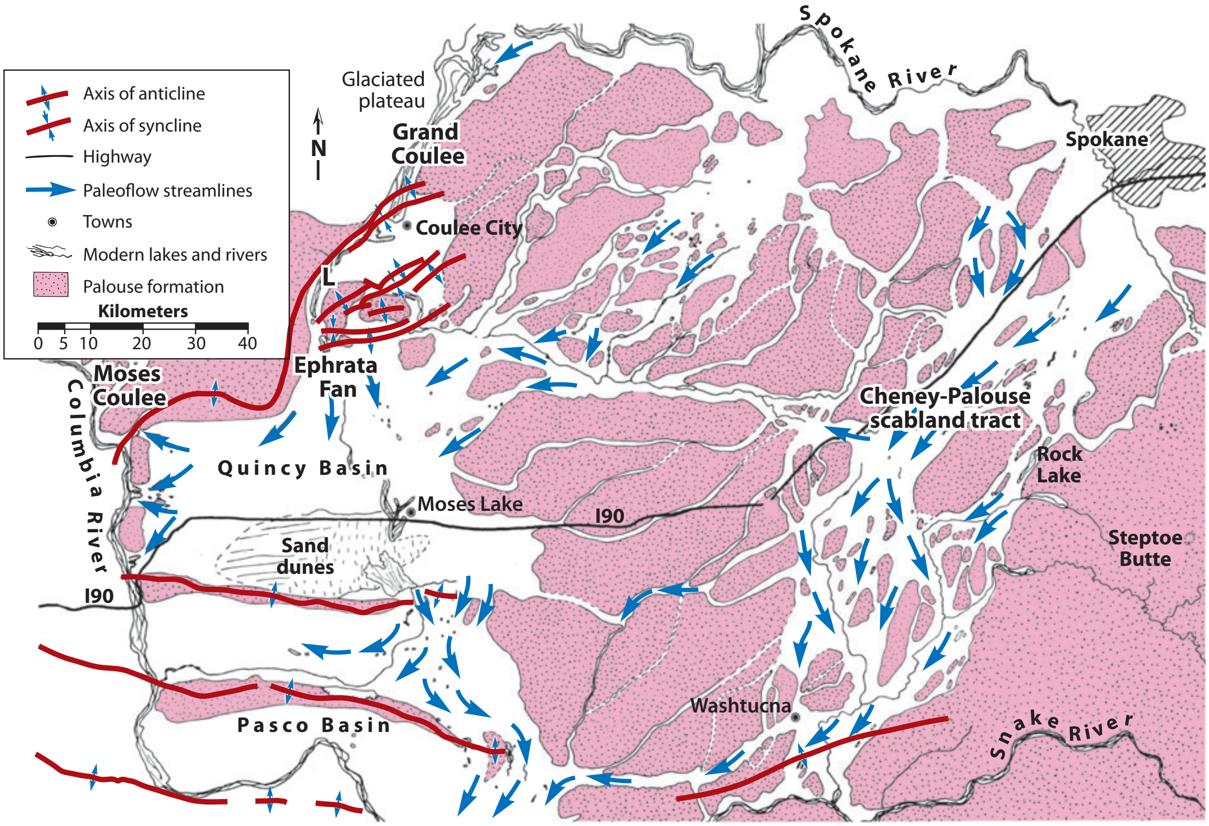

Figure 2

Regional pattern of channels in the Channeled Scabland as interpreted from LANDSAT imagery (E-1039-1843-5 and E-1004-18201-7) showing locations of features discussed in text.

THE SPOKANE FLOOD CONTROVERSY

Named the Spokane Flood, Bretz's (1923b) proposed cataclysm neatly accounted for numerous interrelated aspects of the Channeled Scabland landscape and nearby regions. Nevertheless, the geological community largely resisted his bold hypothesis for decades, despite an enthusiastic, eloquent defense thereof (e.g., Bretz 1927, 1928a). Resolution of the controversy came gradually, initially with the recognition by Pardee (1942) of a plausible source for the huge amounts of floodwater. Pardee showed that ice-dammed Pleistocene glacial Lake Missoula, holding ~2600 cubic kilometers of water, formed in northern Idaho and western Montana and subsequently drained very rapidly to the Channeled Scabland. Eventually, the accumulating field evidence became overwhelming, particularly when Bretz et al. (1956) synthesized new data obtained by the Bureau of Reclamation during the development of the Columbia Basin Irrigation Project in the 1950s. Especially important for convincing the skeptics was the discovery that giant current ripples (GCRs; i.e., fluvial dunes) cap many of the scabland gravel mounds that Bretz had correctly interpreted in the 1920s to be river bars. By the 1960s and 1970s, as evidence mounted (Bretz 1959, 1969; Malde 1968) and as advances occurred in the understanding of the physical processes of cataclysmic flooding (Baker 1973a,b), Bretz's bold hypothesis came to be generally accepted (e.g., Richmond et al. 1965). More recent work has shown that the Channeled Scabland was indeed

UNIFORMITARIANISM

Uniformitarianism is a regulative principle or doctrine in geology that unfortunately sometimes conflates (*a*) the pragmatic application of modern process studies to understanding the past (actualism) with (*b*) substantive presumptions that deny effectiveness to cataclysmic events. As recognized by William Whewell, who invented the term, meaning *b* is contrary to the logic of science (Baker 1998).

produced by megaflooding (flows with peak discharges of at least 1×10^6 m^3 s^{-1}) (Baker 1973a) and that the late Pleistocene flooding occurred repeatedly (Waitt 1980, 1985; Baker & Bunker 1985; Benito & O'Connor 2003).

The prolonged nature of the Spokane Flood controversy arose in part because of the adherence of many geologists to substantive and epistemological presumptions of uniformitarianism (see sidebar) that were erroneously thought to underpin their science (Baker 1998). According to a common, mistaken application of the uniformitarian principle, cataclysmic processes, like those responsible for the origin of the Channeled Scabland, were considered to be unsuitable topics for scientific investigation. To counter this presumption of uniformitarianism, Bretz could only provide meticulously described field evidence for inspection by those willing to seriously consider it. The eventual triumph of his hypothesis, against its initially antagonistic reception, set the stage for the resurgence of a new understanding of geological catastrophism, which is perhaps most prominent today in the acknowledged role of impact cratering in Earth's history.

CHANNELED SCABLAND MORPHOLOGY

Bretz (1923a) first described scablands as lowlands distinguished from nearby Palouse Hills of unconsolidated loess cover by deep fluvial erosion into the underlying basalt bedrock of the Columbia Plateau. This resulted in "...a multiplicity of irregular and commonly anastomosing channels and rock-basins..." (Bretz 1923a, pp. 577–78). The word scabland had been in local use to refer to the absence of soil caused by the flood erosion through the loess cover on the plateau. The most common landform in the eroded rock of scabland tracts is butte-and-basin topography (**Figure 3**). The usual development is small channels and rock basins surrounding buttes and mesas with a typical relief of 30 to 100 m. The rock basins range in scale from shallow saucers or deep potholes, 10 to 100 m in width, to Rock Lake, a huge inner channel that is 11 km long and 30 m deep.

Coulees and Cataracts

In the northwestern United States, the term coulee is applied to very large, steep-walled, trench-like troughs that generally contain no stream along the valley floor. These are commonly the spillways and flood channels of the overall scabland plexus, and many were parts of preflood fluvial valleys that formerly were less deeply incised into the basalt plateau. Hanging valleys occur where the tributaries to these valleys are no longer graded to the main valley floor because of the floor's deepening and widening by the cataclysmic flood scour. Examples occur in Moses Coulee and Lenore Canyon, where the preflood tributaries enter cliff faces on the coulee margins at elevations of 100 or more meters above the coulee floor.

The most famous of the cataract complexes of the Channeled Scabland is located near Coulee City, ~30 km north of Soap Lake, Washington. Named Dry Falls, it consists of four major alcoves

Figure 3

Butte-and-basin scabland developed in Lenore Canyon. Note the roadways for scale.

extending over a width of 5.5 km, each with a vertical drop of ∼120 m. It occurs at the northern end of Lenore Canyon, which was excavated by cataclysmic flood water from a zone of fractured basalt along the axis of the Coulee Monocline (Bretz 1932). It is also at the upstream terminus of an inner channel that receded headward into the Hartline Basin near Coulee City, Washington. The local setting shows the whole assemblage of erosional forms, including longitudinal grooves, potholes, and an inner channel that heads in a cataract complex (**Figure 4**).

Gravel Fans and Bars

Fan complexes occur where constricted cataclysmic flood channels debouche into large structural basins. A well-developed example occurs where the floodwaters from the lower Grand Coulee expanded into the wide Quincy Basin in the west-central part of the Channeled Scabland (**Figure 2**). This is the Ephrata Fan, which has been alternatively interpreted as (*a*) an immense subfluvial expansion bar complex deposited at maximum flood stage and modified by subsequent erosive flows (Baker 1973a) or (*b*) an outwash plain formed by the coalescence of multiple bars emplaced by multiple jökulhlaup floods (Rice & Edgett 1997).

Bretz (1923b) provided the first interpretation of the Channeled Scabland's large mounded scabland gravel deposits as fluvial-emplaced gravel bars. Great depths of water were required to submerge these bars, an interpretation that was also consistent with the indicated crossings of divide areas by the floodwaters. Because there is no universally accepted classification for fluvial bars, a scheme has evolved for local use in the Channeled Scabland and adjacent areas. The scheme is based on the relationship of the bars to large-scale flow patterns in a local scabland channel reach, as recognized by Bretz (1928b), Bretz et al. (1956), and Baker (1973a, 1978b). Longitudinal bars are elongated parallel to the predominant flow direction, and they commonly alternate at the bends of the paleomeanders in scabland valleys that were transformed to flood channel ways. Longitudinal bars commonly develop immediately downstream of bedrock projections on the scabland channel floors, a relationship for which Malde (1968) introduced the term pendant bar. Eddy bars occur at the mouths of alcoves or valleys that were tributary to the valleys that were invaded by the megaflooding. Along the eastern margins of the Cheney-Palouse scabland tract, nearly every tributary valley is blocked at is mouth by this kind of bar (Bretz 1929). As with alluvial rivers, scabland bars are macroforms, in the sense of Jackson (1975) and Church & Jones (1982), such that their dimensions scale to channel widths.

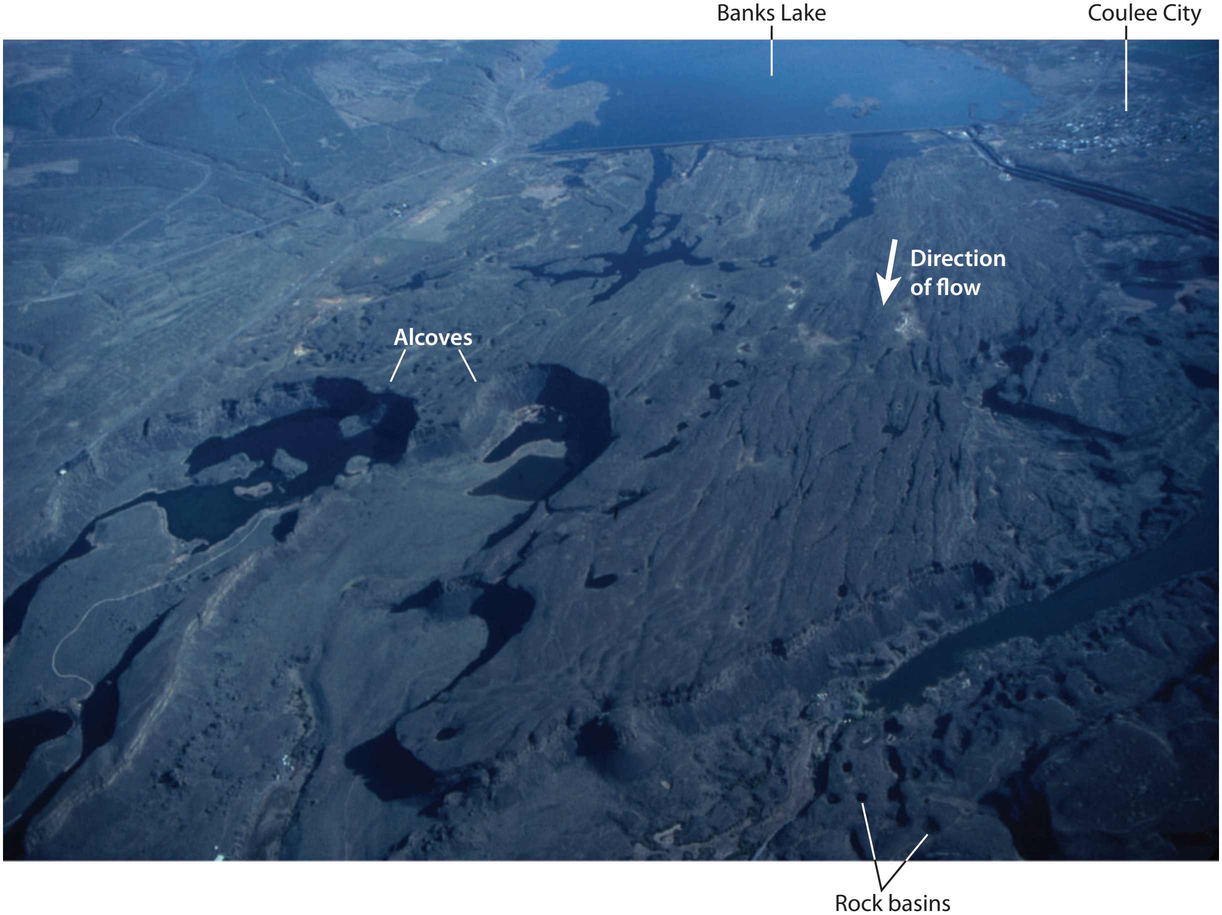

Figure 4

Oblique aerial view of the Dry Falls area. Prominent longitudinal grooves are developed upstream of the cataract. Flow was from top to bottom in this scene, parallel to the grooves. Two prominent alcoves are in the left center of the photo. Note the prominent rock basins (potholes) at the lower right. Banks Lake and its dam are at the top center, and Coulee City is in the upper right corner of the picture.

Many coarse gravel-transporting alluvial rivers assume a braided pattern in which linguoid and transverse bars form with relatively low profiles. Such rivers have relatively high width-to-depth ratios for their channel cross sections. Scabland channel ways, in contrast, experienced very deep flood flows. As a consequence, scabland bars are tens of meters in height, with an internal structure of foreset bedding (Bretz et al. 1956, Baker 1973a). Some of the bars display an accretionary internal structure that indicates a history of multiple emplacing flow events (**Figure 5**) (Baker & Bunker 1985, Benito & O'Connor 2003).

Streamlined Residual Hills and Islands

Bretz (1923b) first recognized the importance of the streamlined shapes for scores of isolated hills of loess, surrounded by scabland, which are most common in the eastern portions of the Channeled Scabland. The steep, ungullied bounding hillslopes of these kilometer-scale hills and islands converge to distinct prow-shaped terminations, producing an overall airfoil-like shape that

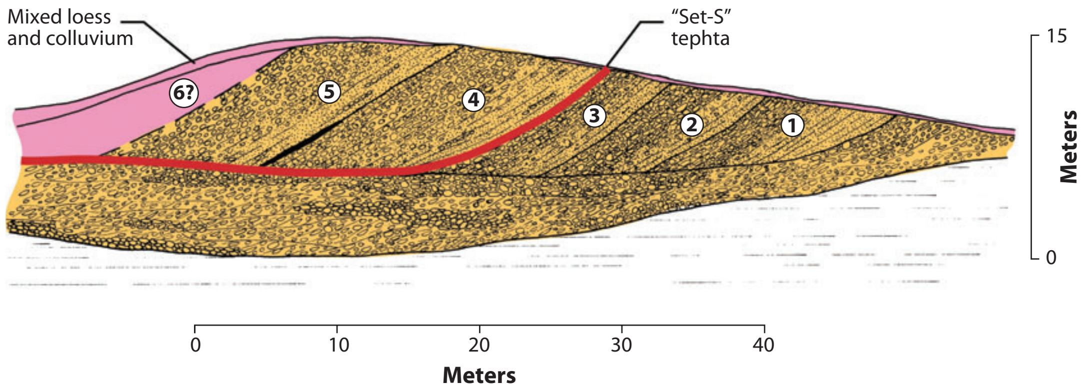

Figure 5

Cross-sectional view of gravel bar near Arlington, Oregon, showing the stratigraphic position of foreset-like beds (*numbered*) and the location of the Mount St. Helens set-S ash layer. The ash and a sandy silt layer of possible subaerial origin (*black unit* between beds 4 and 5) provide probable evidence of significant time periods between subsequent flood events.

is oriented with generating cataclysmic paleoflood flows. The hills are underlain predominantly by loess that was not stripped from the underlying basalt by the floodwaters, but they may also have components of calcified gravels and other sediments. They rise up to 50 m above the surrounding scabland areas, and they generally occur in local clusters, organized in a braid-like pattern of islands within the overall scabland complex. Associated scabland features include eroded rock basins, pendant bars, longitudinal scour zones, and GCRs (subaqueous fluvial dunes) (Patton & Baker 1978a) (**Figure 6**).

Baker (1973b) compared the planimetric shapes of these hills to the lemniscate form used by Chorley (1959) in a study of glacial drumlins. In a more detailed study of the lemniscate, Komar (1984) found that it provides a close representation of symmetric airfoils and can therefore serve in analyses of streamlined landforms. Measurements of numerous scabland streamlined hills (Baker & Kochel 1978) revealed distinctive relationships among lengths, widths, and areas for the landforms (e.g., **Figure 7**), which Baker (1979) hypothesized to be an adjustment of the landform to minimize flow resistance (drag) as it evolved under the influence of the flood erosion. Komar (1983) subsequently showed, in a series of flume experiments, that fluvial erosion processes lead to equilibrium forms through drag minimization.

Giant Current Ripples (Dunes)

Bretz et al. (1956) applied the name giant current ripples to the mesoscale transverse gravel depositional forms of the Channeled Scabland. Following Pardee's (1942) discovery of similar features in the basin of Glacial Lake Missoula, Bretz et al. (1956) identified approximately a dozen examples. Subsequently, Baker (1973a) documented 60 of the most prominent sets of GCR forms. Unpublished work indicates that there are certainly well over 100 GCR occurrences throughout the regions impacted by Missoula megaflooding. The scabland GCRs have a striking appearance on aerial photographs (**Figure 8**) that arises from local postdepositional factors, including eolian silt deposition in the ripple swales and related variations in vegetation cover. An inventory by Baker (1973a) shows (*a*) the GCRs occur in trains of 20 or more, (*b*) their chords (spacings) range from 20 to 200 m, and (*c*) their heights range from 1 to 15 m. In plan view, the GCRs have crest lines that look similar to those of sand ripples in rivers. However, sand ripples typically have chords up to only a few tens of centimeters and heights of several centimeters. In contrast, their scale and

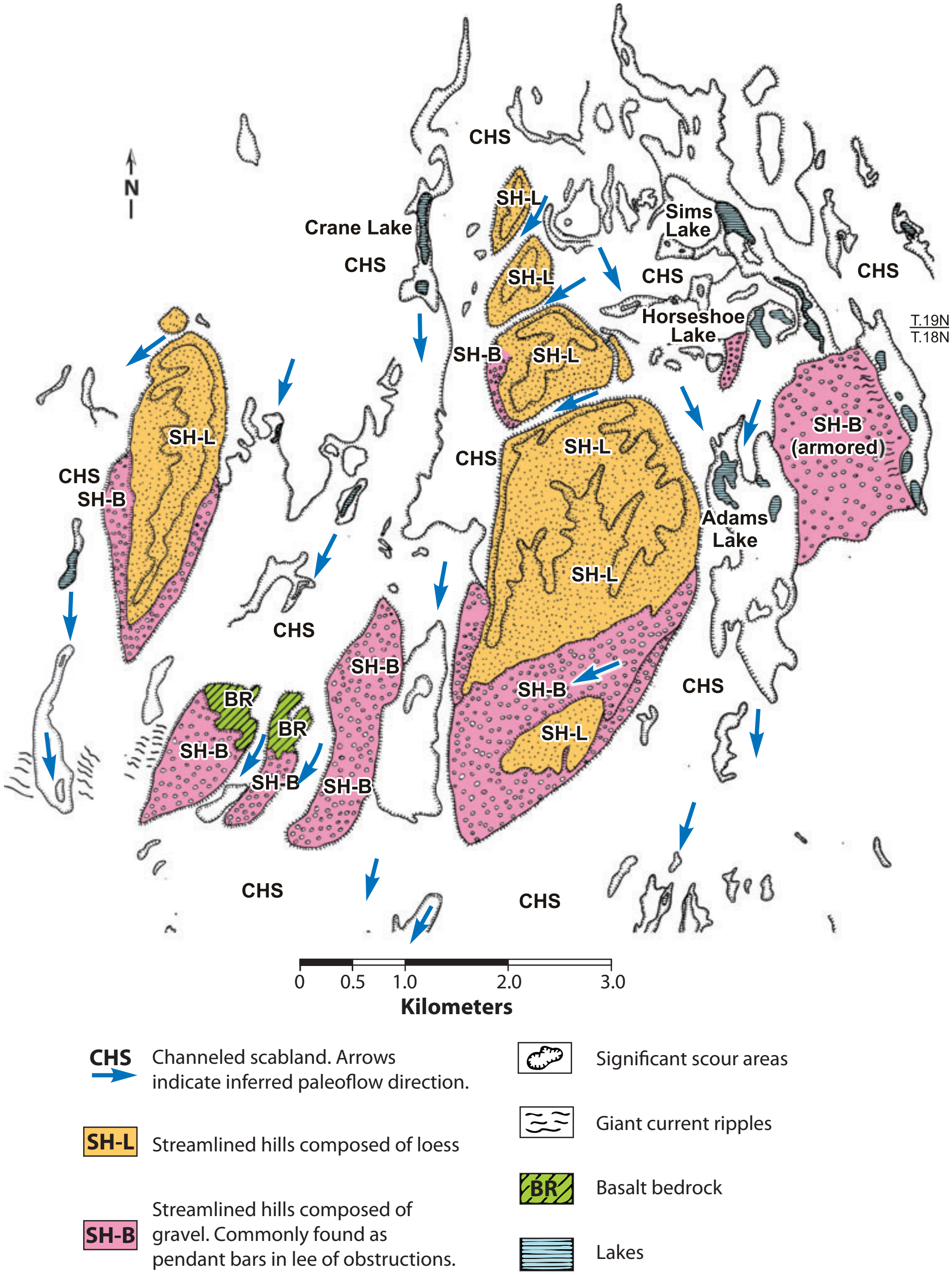

Figure 6

Geomorphological map of a portion of the Macall area in the Cheney-Palouse scabland tract. Note the arrangement of streamlined loess hills, scoured basalt, gravel bars, and giant current ripples (dunes).

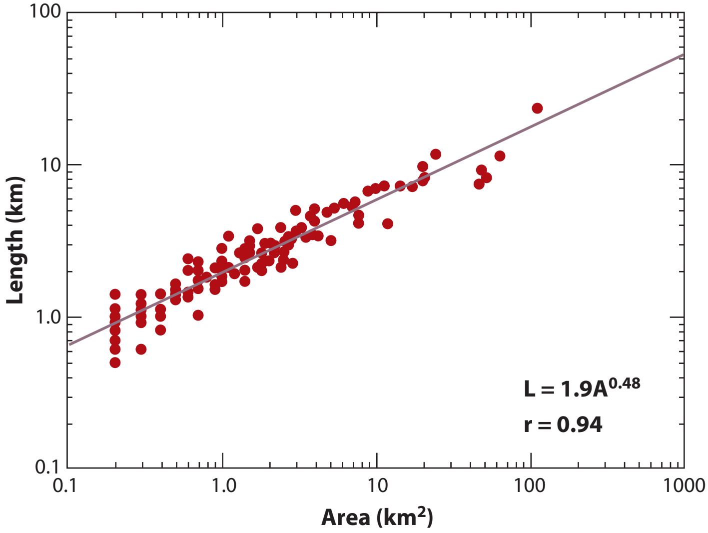

Figure 7

Lengths of scabland streamlined hills and islands versus their areas, as determined by Baker & Kochel (1978).

relation to paleoflow magnitudes indicate that the GCRs are fluvial dunes (Carling 1999). They are composed of gravel, cobbles, and boulders, with an internal structure of foreset bedding and openwork gravel textures.

HIGH-ENERGY MEGAFLOOD PROCESSES

Evolutionary Erosion Sequence

Experimental studies of fluvial erosion in simulated bedrock provide insights into the sequence of erosion forms displayed in the Channeled Scabland. Shepherd & Schumm (1974) and Wohl & Ikeda (1997) found that longitudinal grooves are the first features to form on flume beds of cohesive

Figure 8

Aerial view of giant current ripples (fluvial dunes) near Marlin, Washington (*upper left center*). These bedforms are superimposed on a large gravel bar that lies on the north margin of modern Crab Creek valley (*center*). Flood flows were from east (*left*) to west (*right*). The largest dune forms have heights of ~2 to 3 m and a spacing of up to 60 m (Baker 1973a).

sand-clay mixtures. The grooves gradually evolve into an irregular series of potholes, and the whole surface is subsequently incised to form a prominent inner channel that may migrate upstream by knickpoint recession. By analogy, erosion by cataclysmic water into the Columbia Plateau can be envisioned as occurring in an organized sequence of stages (**Figure 9**), and examples of each hypothesized stage can be found throughout the Channeled Scabland. In the first stage, invading floodwater encounters a plateau surface capped by loess that was shaped into hills by the gentle dissection of streams fed by rainfall and runoff on the plateau itself. The high-velocity water quickly fills the relatively small preflood valleys, shaping the remnant of loess divides between them into streamlined loess hills (**Figure 9**, Phase II). As the floodwater encounters the resistant top portions of an underlying basalt flow, it may initially erode that surface by the action of longitudinal roller vortices (Baker 1978b, 1979), thereby generating longitudinal grooves, such as those observed near Dry Falls (**Figure 4**). As the scour cuts deeper into a basalt flow, it next encounters the well-developed columnar jointing in the basalt. The joint-bounded columns are susceptible to plucking-type erosion (**Figure 9**, Phase III) in which the pressure fluctuations associated with vertical vortices (kolks) lift sections of column and entrain them into the flood water. The plucking erosion first generates large potholes, which then enlarge and coalesce (**Figure 9**, Phase IV) to comprise the commonly observed butte-and-basin scabland topography of the region (**Figure 3**). Eventually, a prominent inner channel (**Figure 9**, Phase V) develops, probably by the initiation and headward migration of a cataract, such as Dry Falls (**Figure 4**).

Kolk: a vortex with a near vertical axis that develops in high-energy flood flows and generates intense pressure gradients that can lift rock particles

Manning equation: formula for the calculation of mean flow velocity (or discharge) under conditions of steady, uniform flow

Cavitation: formation of vapor bubbles by pressure reduction in very fast-moving water flow. Implosion of bubbles at flow boundaries results in immense, local stresses

Hydraulic plucking: water erosion by the detachment and entrainment of large rock fragments by pressure fluctuations in high-energy flows

Power per unit area of bed: product of bed shear stress and mean flow velocity. It is directly proportional to discharge and energy slope, but inversely proportional to the flow width

Paleohydraulics

Early estimates of the flow discharges responsible for the Channeled Scabland features employing the Manning equation (Bretz 1925, Pardee 1942) were subsequently improved by systematic slope-area calculations (Baker 1973a). The latter relied on the exceptionally well-preserved high-water-mark evidence for the paleoflood stages. The flow profile of the Cheney-Palouse scabland tract (**Figure 10**) illustrates how this evidence was used to reconstruct the water surface for the maximum paleoflood stage. The slope-area estimates and subsequent one-dimensional step-backwater calculations (O'Connor & Baker 1992, Benito & O'Connor 2003) generated the parameters necessary for understanding the basic hydraulics of the flood flows (Baker 1973a, 1978c) and their relationships to erosional and depositional features (Baker 1973a,b, 1978b; Benito 1997). Two-dimensional hydraulic modeling, first attempted for the Channeled Scabland by Craig (1987) and now improved by advances in computational power (Miyamoto et al. 2006, 2007), hold particular promise for future progress.

Bedrock Erosion Processes

High-energy water flows are conventionally considered to erode rock by various processes, including abrasion (corrasion), corrosion, cavitation, fluid stressing, physical weathering, and plucking (Richardson & Carling 2005). Of these, hydraulic plucking of the jointed bedrock is considered to be of major importance for the origin of the Channeled Scabland (Bretz 1924; Bretz et al. 1956; Baker 1973b, 1978c, 1979). Benito (1997) correlated the scabland sequence of erosional forms (**Figure 9**) to various measures of flow strength in the megaflooding, including velocity, flow depth, and power per unit area of bed. Values for the latter ranged from 500 to 2000 watts m^{-2} for Phases I and II (**Figure 9**) to 5000 to 25,000+ watts m^{-2} for Phases IV and V (**Figure 9**). However, these are only suggestive empirical associations. Work is needed on the actual physical mechanisms of erosion, elucidation of which is of considerable importance for understanding modern bedrock erosion processes (Tinkler & Wohl 1998, Whipple et al. 2000).

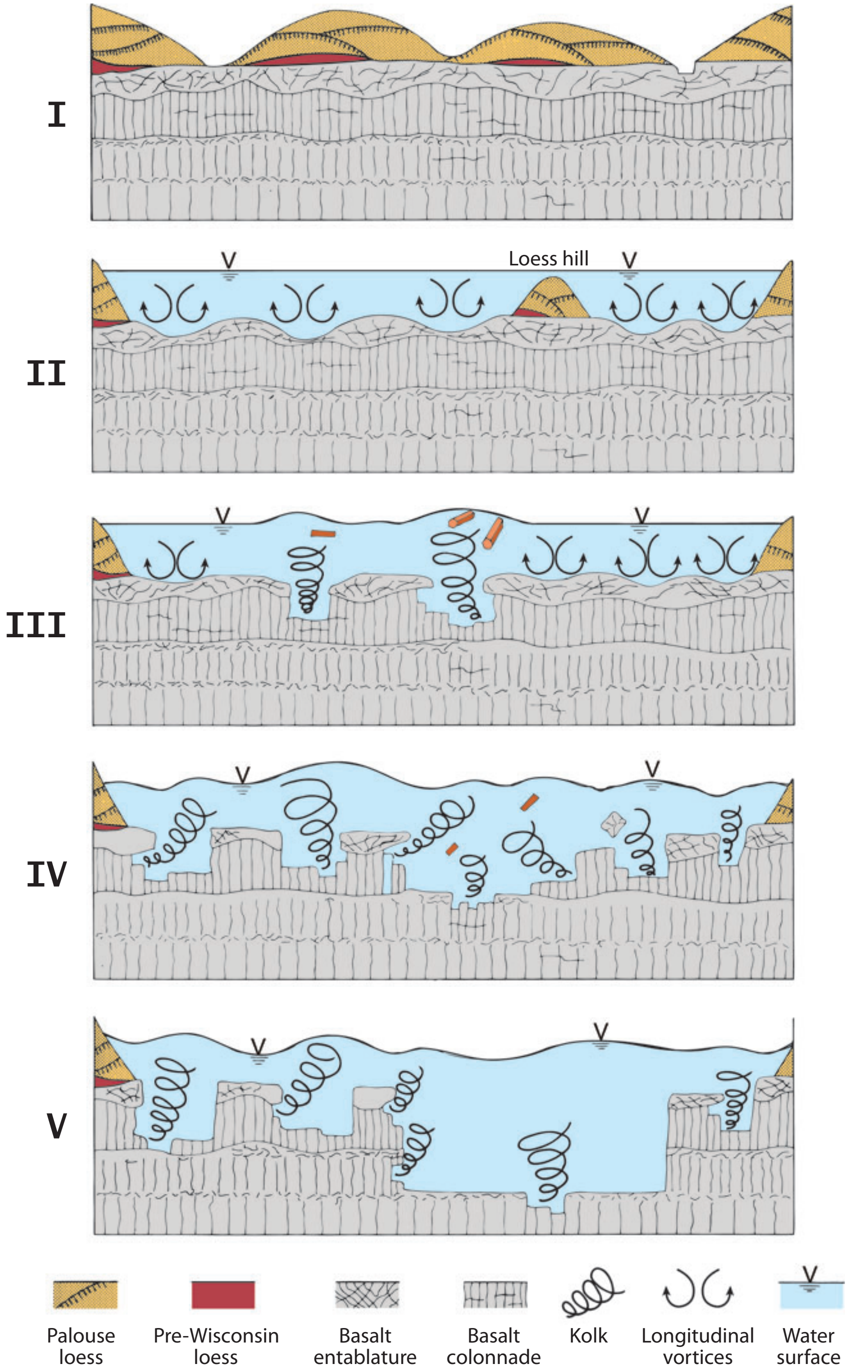

Figure 9

Inferred sequence of erosion for the Channeled Scabland illustrated by schematic cross sections.

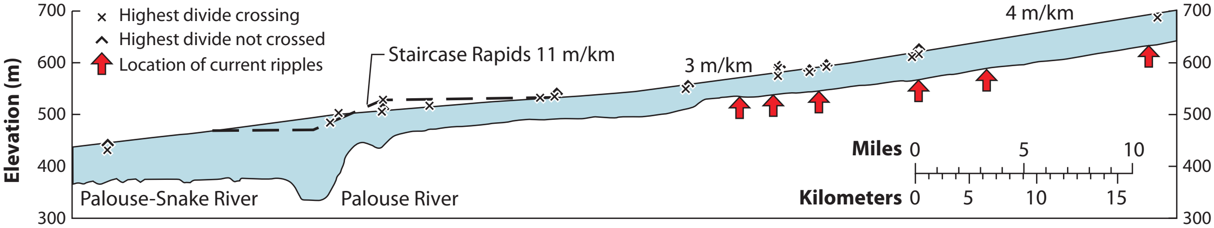

Figure 10

Flow profile along a portion of the Cheney-Palouse scabland tract that shows the use of various high-water marks in reconstructing the paleowater surface during the flooding.

Sediment Transport

Bed shear stress: measure of flow strength determined by the product of fluid density, gravitational acceleration, flow depth, and energy slope

Hyperpycnal flow: flowing water that is denser than the standing body of water that it enters, thereby resulting in a density underflow

The scabland megaflooding exhibited phenomenal sediment transport capability, as evidenced by the boulders that were entrained by the flow (**Figure 11**). Early work emphasized the competence of flows to initiate the movement of such particles (Baker 1973a, Baker & Ritter 1975), but another approach is to consider the paleohydraulic conditions associated with deposition of the boulders during conditions of high-energy flooding (O'Connor 1993). Also interesting are the effects of very high-energy flow conditions on the ranges of particle sizes that can be transported as bedload, suspended load, and washload (autosuspension load). From considerations outlined by Komar (1980, 1988), O'Connor (1993) found that above sustained bed shear stresses of 1000 N m^{-2}, particles as large as 10 to 20 cm move in suspension and coarse sand moves as washload. A more conjectural extension of Komar's (1980, 1988) analyses by Komatsu & Baker (1997) suggests that at the phenomenally high bed shear stresses of 10^4 to 10^5 N m^{-2}, achieved by the most energetic scabland flooding (Baker & Costa 1987, Baker & Komar 1987), boulders up to several meters in diameter could have been transported in suspension.

Upon reaching the Pacific Ocean, the Missoula floodwaters continued flowing down the continental slope as hyperpycnal flows and associated turbidity currents (Normark & Reid 2003).

Figure 11

Large boulder deposited by cataclysmic flood water on the proximal part of the Ephrata fan. It measures ~18 m on its long axis and was transported from basalt outcrops ~10 km away. A prominent scour hole, described by Baker (1973a, 1978b), extends downstream from the boulder.

The sediment-charged floodwaters followed the Cascadia submarine channel into and through the Blanco Fracture Zone and out onto the abyssal plain of the Pacific. As much as 5000 km^3 of sediment may have been carried and distributed as turbidites over a distance of 2000 km west of the Columbia River mouth.

MEGAFLOODS AS GLOBAL PLANETARY PHENOMENA

Bretz thought the landforms of the Channeled Scabland to be unique (Bretz 1928a). "Nowhere in the world is there known or suspected," he wrote (Bretz 1959, p. 56), "a story at all comparable to what we read from the scabland forms." He reasoned that its uniqueness might make his Spokane Flood hypothesis more acceptable to those who held to the generalization that landscapes are created by the prolonged action of noncataclysmic processes. In recent years, however, cataclysmic flood landscapes with many similarities to the Channeled Scabland have increasingly been documented in many parts of the world (Baker 1997, 2002, 2007). Spectacular examples of GCRs are found in central Asia (Baker et al. 1993, Carling 1996, Rudoy 2005), along with immense gravel bars and scour marks (Rudoy & Baker 1993, Carling et al. 2002, Herget 2005). Megaflood streamlined hill morphologies occur in the glacial lake spillway channels of central North America (Kehew & Lord 1986) and on the floor of the English Channel (Gupta et al. 2007). Most surprising to Bretz, however, would be the discovery of scabland-like morphologies on Mars (Baker & Milton 1974; Baker 1982, 2001; Komatsu & Baker 2007).

In addition to stimulating discoveries of cataclysmic flood landscapes, studies of the patterns, forms, and processes evident in the Channeled Scabland have informed understanding of processes that occur at smaller scales in modern bedrock channels that are impacted by extreme, high-energy floods (e.g., Baker 1977, 1984; Baker & Pickup 1987; Baker & Kochel 1988; Baker & Kale 1998). Slackwater deposition by scabland flooding at the mouths of various valleys tributary to the Cheney-Palouse scabland channels (Bretz 1929, Patton et al. 1979) was used to infer flow depths along those channels (**Figure 10**). This methodology proved to be critical in stimulating the development of that form of paleoflood hydrology that utilizes paleostage indicators for the reconstruction of relatively recent (late Holocene) floods, thereby increasing our understanding the frequencies of rare, modern high-magnitude floods (Baker 1987, 2006, 2008b). Indeed, one can envision a kind of investigation that inverts the usual reasoning process whereby studies of common, small-scale processes are extrapolated to the domain of less common, unobserved large-scale processes.

DISCUSSION AND FUTURE CHALLENGES

In addition to the megaflood process issues noted above, there remain many unresolved questions in regard to the Channeled Scabland and its origin, including the following:

1. The late Pleistocene phase of flooding is currently considered to have occurred over a period of a few thousand years, centered ~17,500 to 14,500 calendar years before present (Waitt 1985, Atwater 1986), as constrained by studies of associations of various flood deposits with the Mount St. Helens set-S tephra (Moody 1978; Mullineaux et al. 1978; Waitt 1980, 1985; Bunker 1982; Busacca et al. 1992). However, there is some evidence that the cataclysmic flooding occurred a few thousand years earlier, based on uncertainties in the set-S chronology (Berger & Busacca 1995, Beget et al. 1997, Clague et al. 2003) and recent radiocarbon dating results (Benito & O'Connor 2003). Opportunities exist to apply additional geochronological tools, including cosmogenic nuclide exposure dating (Gosse & Phillips 2001) and luminescence dating (Lian & Roberts 2006). Moreover, the clear indications of earlier Pleistocene flooding (Bretz et al. 1956, Patton & Baker 1978b, McDonald &

Busacca 1988, Baker et al. 1991) have yet to be integrated into the picture, though progress has been made by employing magnetostratigraphy and uranium series dating (Bjornstadt et al. 2001, Pluhar et al. 2006).

2. The late Pleistocene flooding through the Channeled Scabland and adjacent areas involved multiple events, perhaps 40 to 100 or so, as indicated by low-energy (silt and sand) facies of flood-related deposition into various basins, backwater areas, and ice-marginal lakes (Waitt 1980, 1984, 1985; Atwater 1986, 1987; Smith 1993). Studies of high-energy (gravel and boulder) facies (e.g., **Figure 5**) suggest that many of these hypothesized floods were probably of relatively low magnitude in comparison with the biggest events (Baker & Bunker 1985, O'Connor & Baker 1992, Benito & O'Connor 2003). Work is needed to sort out the complete magnitude and frequency picture for scabland flooding, tracing the flood indicators all the way from the paleo-ice-sheet margins to deposits on the ocean floor (e.g., Brunner et al. 1999, Zuffa et al. 2000).
3. Although glacial Lake Missoula clearly provided a source for the late Pleistocene flooding of the Channeled Scabland, many questions remain in regard to the mechanism for its ice-dam failures (Clarke et al. 1984, O'Connor & Baker 1992), the nature and history of lake fillings and drainings (Chambers 1984, Levish 1997, Smith 2006), and inferred correlations of lake sediments to downstream flood sediments (Waitt 1985).
4. Recent two-dimensional modeling results (Komatsu et al. 2000; Miyamoto et al. 2006, 2007) indicate that the maximum volume of water stored in glacial Lake Missoula ($\sim$2600 km^3) is insufficient to account for the indicated levels of maximum inundation throughout the Channeled Scabland and adjacent area. Can this anomaly be explained by the multiple pathways taken by different outburst floods and/or by the varying nature of downstream controls on that flooding (Benito & O'Connor 2003)? Alternatively, does this result imply that non-Missoula sources are involved, such as subglacial outburst flooding from under the Cordilleran Ice Sheet, as proposed by Shaw et al. (1999)? The latter hypothesis certainly conflicts with current understanding (Atwater et al. 2000). Nevertheless, knowledge of subglacial flooding is being transformed by recent discoveries concerning Antarctic subglacial lakes (Wingham et al. 2006, Fricker et al. 2007). Scabland-like landforms are inferred to have been generated by megaflooding from beneath ancient Antarctic ice sheets (Denton & Sugden 2005, Lewis et al. 2006). Could the Channeled Scabland have a similar component to its origin?

In retrospect, studies of the Channeled Scabland might be viewed as concerned with the unique origins of a single landscape. However, this remarkable landscape was not studied to test a preexisting hypothesis or theory (e.g., erosion and deposition by high-energy megaflooding). Instead, discoveries about the Channeled Scabland are leading scientific inquiry to the recognition of what can now be seen as related phenomena, such that a completely new theory is required. The resulting rich set of research opportunities traces back to a single imaginative hypothesis proposed in the 1920s by J Harlen Bretz. Though these opportunities may now be pursued with techniques that to Bretz would have seemed almost magical, the most important pathway to advancing understanding remains that which is best exemplified by Bretz's most lasting contribution: informed and insightful geological fieldwork.

DISCLOSURE STATEMENT

The author is not aware of any biases that might be perceived as affecting the objectivity of this review.

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