CATASTROPHIC FLOOD FEATURES AT CAMAS PRAIRIE, MONTANA
More *Unusual Currents in Glacial Lake Missoula*

CATASTROPHIC FLOOD FEATURES AT CAMAS PRAIRIE, MONTANA

More *Unusual Currents in Glacial Lake Missoula*

KEENAN LEE

DEPARTMENT OF GEOLOGY AND GEOLOGICAL ENGINEERING
COLORADO SCHOOL OF MINES

GOLDEN COLORADO 80401

2009

CONTENTS

ABSTRACT

Camas Prairie preserves landforms and bedforms that document catastrophic currents at the bottom of glacial Lake Missoula when its glacier dam broke. Although similar features occur in the scablands of eastern Washington, the currents there were channeled floods that flowed downhill; here the sublake currents often flowed uphill. Similar catastrophic lake-bottom currents have been documented elsewhere only in the Altai flood of Siberia.

When the ice dam failed and flooding began, the northern rim of the Camas Prairie Basin and part of the eastern rim were under water, forming sublake divides, or ridges. All flow into the basin came over the basin rims, and all of the lake-bottom currents were flowing uphill to enter the basin. As lake level fell, bottom currents were increasingly concentrated in four inlet sublake notches, formerly and currently topographic passes. The notches were catastrophically eroded as blocks of bedrock were torn out by vertical vortices, or kolks, that produced jagged bedrock floors, probably in a matter of hours.

Just outside of the basin, bottom currents carried bedload gravels *up* slope toward the sublake notches, depositing them in the lee of obstacles and just over the rim in washover bars. Expansion bars formed high up on the basin rim below each of the sublake notches where foreset beds of open-work boulder-cobble-pebble gravel were deposited, along with fallout blocks of bedrock from dissipating kolk vortices. Closed depressions, or pools, on the surfaces of the expansion bars suggest chute and pool structures.

Camas Prairie floodwaters drained through two outlets, Rainbow Lake Pass to the west and Perma Ridge to the south. Flood currents tore out a long, deep, flat rip channel pocked by kolk pits at Rainbow Lake and deposited flood gravels in several expansion bars. Perma Ridge was severely eroded into a series of stepped rip channels with kolk pits along the west abutment of the basin as flood currents took the most direct route to the failed damsite.

Giant current ripples, or gravel dunes, formed below each of the four inlet sublake notches over an area of at least 10 square miles [26 km^2]. Wavelengths range from 90 to 951 ft with a mean of 270 ft [27-290 m, 82 m], height ranges from 1 to 57 ft with a mean of 12 ft [0.3-17 m, 4 m], ripple index ranges from 14 to 90 with a mean of 31, and asymmetry ranges from 0.2 to 2.8. Based on asymmetry of the dunes and their shape in map view, they can be subdivided into normal, reverse, or antidunes. Normal dunes, the most common in the basin, are two-dimensional with steeper lee slopes, and their shape is generally transverse sinuous in-phase. Reverse dunes have shapes similar to normal dunes, but have steeper stoss sides. Antidunes are three-dimensional, with short, arcuate transverse, convex-downcurrent shapes with steeper stoss sides.

Normal giant current ripples have a mean wavelength of 259 ft [79 m] and a mean height of 11 ft [3 m]. Size decreases away from the notches, but not in a consistent manner. Constituent gravels similarly decrease in size to the south, with open-work fabric and crude foreset bedding that dips from 14 degrees to 23 degrees. Reverse dunes are recognized only below one notch, where they formed on fairly steep slopes, but they may well occur elsewhere. One small train of antidunes formed at each of the expansion bars. Along with their position, their shape is distinct from all other giant current ripples in the basin. No exposure is available to document backset bedding.

Fluvial antidunes and chute-and-pool structures normally are not preserved because waning flows transition into lower flow regimes that modify the bedforms. At Camas Prairie they may be preserved because of the unique paleohydraulic regime, in which current velocities did not decrease in a gradual manner, but dropped abruptly when lake level fell below the sublake notch.

Giant current ripples at Camas Prairie are significantly different from normal sand ripples in more than just size. They show close correspondence to giant current ripples created by the Missoula flood below the ice dam in the scablands of eastern Washington and, even more closely analogous, to giant current ripples formed on the floor of Lake Kuray-Chuya by the Altai flood in Siberia.

INTRODUCTION

In 1942 Joseph T. Pardee published *Unusual Currents in Glacial Lake Missoula*, which became a landmark publication that helped to turn the tide in favor of J Harlan Bretz's hypothesis of a huge flood through Spokane [Bretz, 1969 and references therein; summarized by Baker, 1981]. A key bit of evidence in Pardee's paper was a description of the Camas Prairie, where he documented landforms that could have been produced only by currents of unusual depth and velocity. Pardee's epiphany came when he saw the first aerial photographs of Camas Prairie and recognized giant current ripples. Of the evidence presented in Pardee's paper in 1942, none was as sensational as the aerial photograph showing giant current ripples [see cover for similar photo]. Pardee described them as perfect analogs to stream ripples except for their outlandish size. He posed the question: what else *could* they be except bedforms of immensely powerful currents? A lack of answers forced many flood skeptics to reconsider their positions.

Pardee's interpretation of Camas Prairie was excellent. In this study, better aerial photos were used than those available to Pardee, kindly provided by Seth Makepeace of the Confederated Salish and Kootenai Tribes of the Flathead Nation and Judy Reese of the US Forest Service. Field work checked the photointerpretation and added measurements of the giant current ripples. This study mostly extends mapping and adds detail to Pardee's work. Surprisingly little work has been done in the Camas Prairie since Pardee's study; Lister [1981] measured some of the giant current ripples and compiled data from water wells. Considerably more work has been published to document the catastrophic flood below the ice dam, but those floods were fundamentally different; they were analogous to conventional channel flood flows, driven by release of water upstream that forced the flood downstream. The lake-bottom currents at Camas Prairie, by contrast, were driven by the failure of the ice dam downstream that basically pulled the plug on the lake and forced the flood to progress upstream.

Although it is now clear that the 'Missoula Flood' in reality consisted of numerous floods, there is little evidence for it at Camas Prairie. In a few cases, some deposits suggest different relative ages, but overall the flood features at Camas Prairie do not lend themselves to establishing any chronology.

This report introduces three new aspects to the geology of the area: [1] ubiquitous bedload gravels were transported *up*slope and deposited in the lee of local relief and on the rim of the basin; [2] unusual bedforms - antidunes and chute and pool structures – may be preserved here because of the unique paleohydraulic regime; and [3] the giant current ripples of Camas Prairie differ from normal sand ripples in more than size, and they are quite similar to giant current ripples in eastern Washington and Siberia.

LOCATION AND SETTING

A glacier advanced southward from Canada about 15 000 years ago and dammed the Clark Fork River at Lake Pend Oreille, Idaho, creating glacial Lake Missoula [Pardee, 1910] [Fig. 1]. Glacial Lake Missoula probably had a highstand elevation of 4250 ft [1295 m][Pardee, 1942; Roy Breckenridge, 2003, pers. comm.], which put Camas Prairie under about 1400 ft [430 m] of water at the time the glacier dam at Lake Pend Oreille failed [Fig. 2]. Pardee mapped the extent of glacial Lake Missoula, from which one can see the complex drainage paths of the lake when the ice dam failed. About a third of the total volume of Lake Missoula drained from the northeast, from the Camas Prairie Basin and the Mission and Little Bitterroot Valleys, and much of this flowed through Camas Prairie [Fig.3]. At first there were two main drainage paths, the most direct being through Rainbow Lake Pass and the longer path along the Flathead River through the Perma-Paradise Narrows.

Rainbow Lake Pass was under about 630 ft [190 m] of water at lake highstand. After breakout, when draining of the lake was in full swing, it provided the shortest flow path out of Camas Prairie Basin. When the local lake level dropped enough that Rainbow Lake Pass was abandoned, the main flow turned south through Camas Prairie. During this later stage of flow, water from the north and east drained south through the Camas Prairie Basin to join flood flow in the Flathead River Valley at Perma [Fig 4].

Pardee described the effects of these currents flowing over the north and northeast rims of the Camas Prairie Basin. All of his unusual features at Camas Prairie *appear to have been formed by large currents plunging over the north rim and continuing with decreasing velocity out into the basin. Such currents might have formed when the water surface in Camas Prairie Basin first became lower than the water surface in Little Bitterroot Basin thus causing masses of water to pass over the ridge, chiefly through the gaps* ["sublake notches" of this study] (Pardee, 1942, p. 1588). An aerial view of the north rim of Camas Prairie Basin, looking north into the Little Bitterroot Valley, is shown in Figure 5. The two largest sublake notches are shown, along with their flood features.

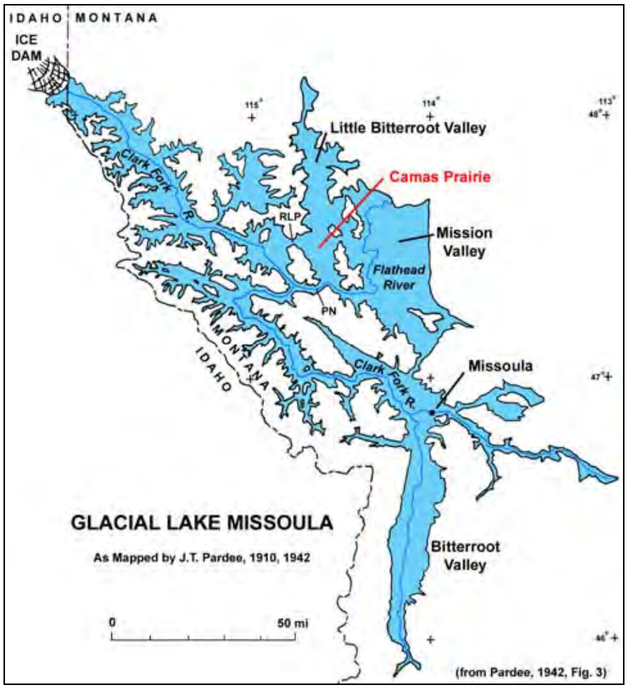

Figure 1—Glacial Lake Missoula at an elevation of 4150 ft [1265 m]. The only outlet for the 500-cubic mile [2000 km^3] lake was to the northwest, where glaciers blocked the Clark Fork River. When the ice dam failed, all of the northeastern part of Lake Missoula, about a third of the total, poured through two gaps at Rainbow Lake Pass [RLP] and the Perma Narrows [PN].

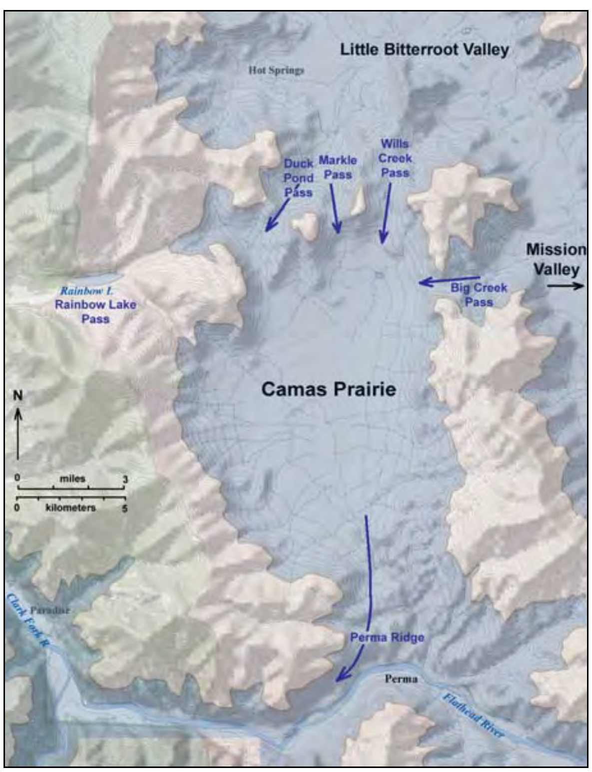

Figure 4—Glacial Lake Missoula when local lake level dropped to 3650 ft elevation and all water drained south through Camas Prairie to rip across Perma Ridge. Inflow increasingly concentrated in the four inlet sublake notches.

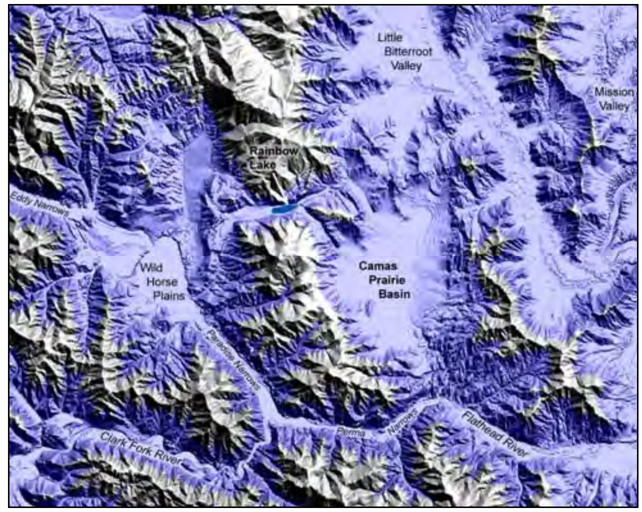

Figure 2— Camas Prairie region showing Lake Missoula at highstand [4250 ft elevation].

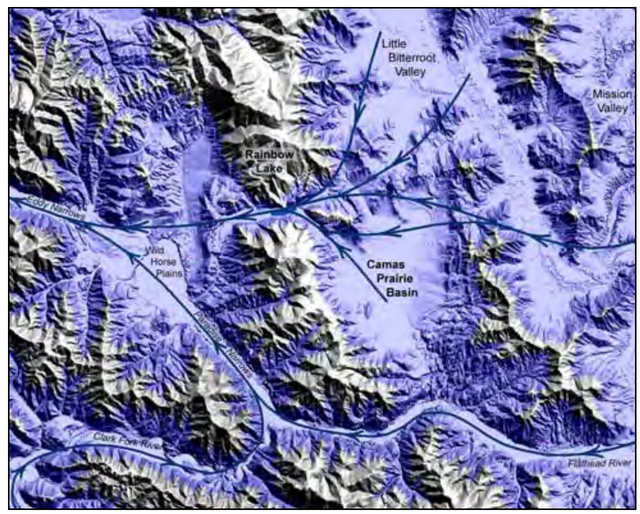

Figure 3—Lake Missoula emptied through the single outlet of Eddy Narrows, first ripping through either Rainbow Lake Pass or Paradise Narrows.

THE CAMAS PRAIRIE BASIN

Camas Prairie is a flat-floored basin surrounded by mountains except where it drains southward into the Flathead River at Perma [Fig. 6]. The basin is slightly elliptical, about 12 miles by 10 miles [19 km by 16 km], with an area of about 100 square miles [260 km^2]. Elevations of the basin floor are slightly below 3000 ft [900 m], and surrounding mountains reach 5000 ft to 6000 ft [1500 m to 1800 m].

The floor of the basin is quite flat; the transition to mountains occurs around 3000 ft [900 m], yet the low area in the center of the basin is about 2800 ft [850 m]. The distinguishing feature of the Camas Prairie Basin floor is the huge field of giant current ripples [see cover, bottom]. From the ground, these are not very apparent; at high sun, one can drive through the basin and note only some low ridges [as Pardee apparently did]. Given the synoptic view of aerial photographs, however, or at the low sun angles of early morning or late afternoon, the giant current ripples are indeed striking [see cover, top]. One can imagine Pardee's incredulity when he received his first air photos!

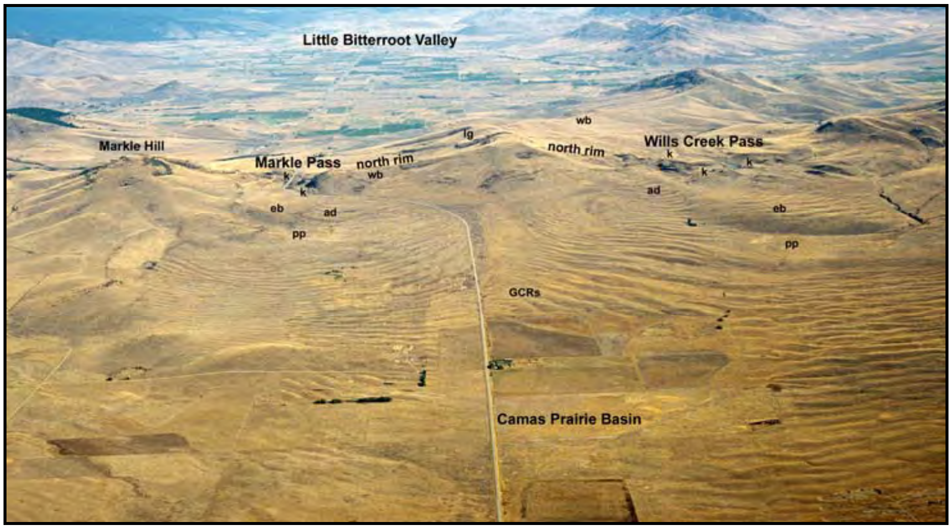

Figure 5–Aerial view to the north of north rim of Camas Prairie Basin. ad, antidunes;eb, expansion bar; GCRs, giant current ripples; k, kolk pits; lg, lee gravels; pp, 'plunge pool'; wb, washover bar.

All rocks exposed in the Camas Prairie Basin belong to the Belt Supergroup, mostly Prichard Formation, which are very competent metasedimentary rocks with intruded basaltic rocks. The original sediments – clays, silts, and sands – came from North America, Australia, and Siberia when the three continents were joined 1.5 billion years ago. They were then metamorphosed by high temperatures and pressures resulting from deep burial [more than 20,000 ft] to argillites, siltites, and quartzites, respectively.

At the highstand of Lake Missoula, the lake surface in Camas Prairie was open to the north and northeast into the Little Bitterroot and Mission Valleys and to the south into the Flathead River Valley. Only a very narrow channel connected the lake to the west with the Clark Fork River Valley. Figure 6 shows the highest shoreline of glacial Lake Missoula, and Figure 7 shows some of the numerous shorelines in the basin, best developed on west-facing slopes that would have received the heaviest surf from westerly storm winds. The present north and northeast rims of the Camas Prairie Basin were, therefore, sublake divides of glacial Lake Missoula.

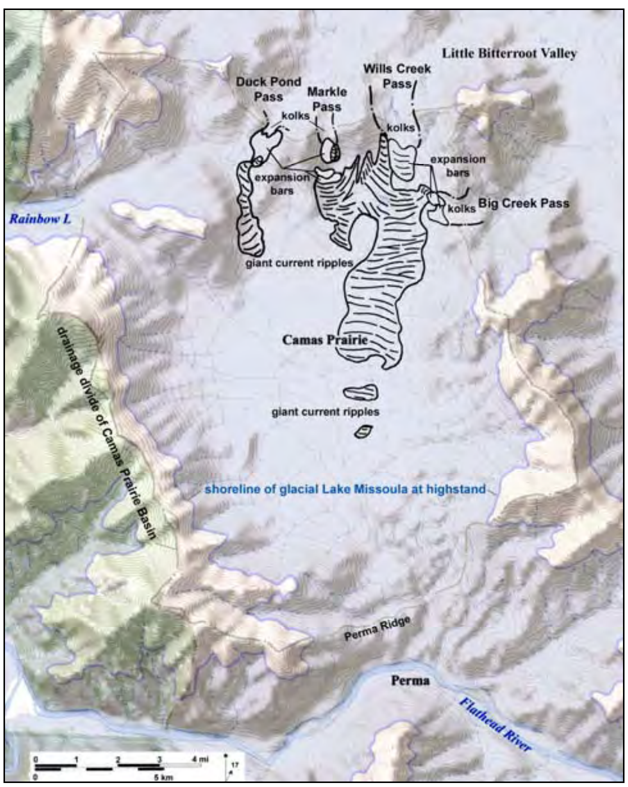

Figure 6—Characteristics of Camas Prairie Basin and catastrophic flood features. Topographic map shows the morphology of the basin, defined by the drainage divide, and Lake Missoula at its highstand. Generalized catastrophic flood features are in black.

Figure 7—Shorelines of glacial Lake Missoula on the eastern side of Camas Prairie Basin. Strike of near-vertical bedrock is shown by the vertical bedding symbols.

Flood flows left the Camas Prairie Basin through two outlets, Rainbow lake Pass in the northwest part of the basin and Perma Ridge in the south. Rainbow Lake Pass today is a long, flat-floored rip channel pocked by kolk pits. At the west end of the rip channel, flood currents were deflected by high bedrock hills and deposited flood gravels in several expansion bars.

Flow through the Perma outlet did not simply follow the then-existing, and current, Camas Creek drainage to the Flathead River. The early torrential outflow took a more direct route to the Flathead River Valley by flowing over a ridge to the west of Camas Creek against the right abutment of the basin divide. This ridge is referred to here as Perma Ridge [see Fig. 4]; the ridge is unnamed on the topographic map. Perma Ridge is characterized by a surface with numerous kolk pits, rip channels, and steep bedrock cliffs. Across the Flathead River from Perma Ridge is an anomalous whamout zone – a term introduced here for a bare bedrock area gouged out by direct impact of a catastrophic flood current - that probably originated from the Camas Prairie flow, either directly from the outflow or from Flathead River flood currents that were forced against the south wall by the Camas Prairie outflow.

INFLOW SUBLAKE NOTCHES AND RELATED FLOOD FEATURES

A generalized model of an inflow sublake notch is given in Figure 8. Lake-bottom currents flowed uphill toward the rim of Camas Prairie Basin, transporting bedload gravels that collected in the lee of local obstructions and in washover bars just over the rim of the basin. Currents concentrated in the former pass tore out bedrock pits and deposited gravels in an expansion bar and in giant current ripples.

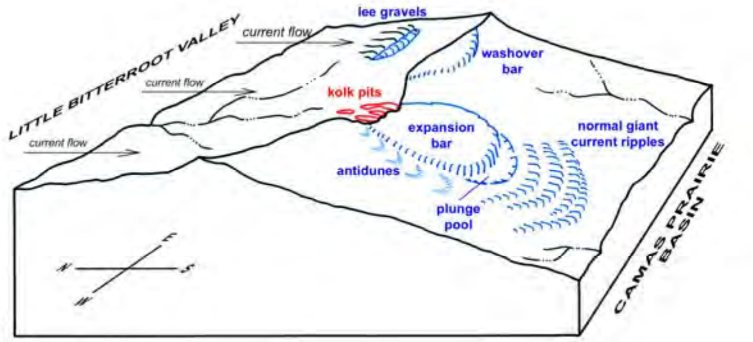

Figure 8—Generalized model of an inflow sublake notch.

Four sublake notches controlled flood flows into the Camas Prairie Basin [Table 1]. The highest is Duck Pond Pass on the northwest part of the basin [see Fig. 4]. Flow through Duck Pond Pass was to the southwest, but a high ridge, almost perpendicular to flow, lay in its path and would have diverted currents, initially to the west through Rainbow Lake Pass, and later to the southeast down Cottonwood Creek [Fig. 6]. Big Creek Pass, on the northeastern side of the basin, received flow from the lower Little Bitterroot and Mission Valleys to the east. As the second highest sublake notch, it was abandoned relatively early. Markle Pass and Wills Creek Pass lie on the north rim of the basin and received flow from the Little Bitterroot Valley.

Table 1—Inflow Sublake Notches at Camas Prairie

Sublake Notch[a]	Depth [ft] Highstand[e]	Depth [ft] Start of Flow 2[f]	Present Elevation
Duck Pond Pass[b]	800 [244 m]	200 [61 m]	3450
Big Creek Pass[c]	840 [256 m]	250 [76 m]	3410
Markle Pass	910 [277 m]	300 [91 m]	3340
Wills Creek Pass[d]	1070 [326m]	450 [137 m]	3180

[a] names used by Pardee [1942] [b] not labeled on topo map
[c] not labeled on topo map, at head of Big Gulch
[d] not labeled on topo map, at head of Wilks Gulch; site of Schmitz Lakes
[e] 4250 ft elevation [suggested by Pardee, 1942, although he used 4150 ft in his calculations; 4260 ft by GPS (Roy Breckenridge, 2003, pers.comm.)
[f] when Rainbow Lake Pass closed

Inflow sublake notches were initially sites of lake-bottom currents that became progressively more concentrated as lake level fell, ultimately to become torrential inflow channels. Within the sublake notches, severe scour took place, producing bare bedrock surfaces similar to the scablands of eastern Washington. J Harlan Bretz [1923] used the term *scablands* to refer to areas of bare bedrock stripped by the Missoula flood with channels cut into the bedrock by a "plucking" action of the floodwaters. The term is used in the same way here, although here the areas of erosion and related deposition are considerably smaller [Fig. 9].

In the most constricted part of sublake notches, numerous pits occur, some of which now retain water. These pits are usually elongate, very angular, and entirely in bedrock. They resulted from extreme erosional processes, but not normal fluvial erosion [one must constantly be reminded that these currents were not fluvial – that is, channel flows, but rather, lake-bottom currents]. The dominant process was not particle impact and abrasion, but a plucking action that cleanly removed blocks of bedrock without causing significant rounding of edges. *Kolks* have been suggested as the main agent for such vertical extractions in the scablands of eastern Washington [Baker, 1973]. Kolks are subvertical, upward vortices that form in very deep and very fast currents, especially in boundary areas of shear, which as a fluid mechanics phenomenon, is similar to tornadic action [Matthes, 1947]. David Alt [2001] likened kolks to underwater tornadoes. Kolks are capable of plucking multi-ton blocks of rock and transporting them in suspension for thousands of feet. Evidence of kolks consists of plucked-bedrock pits and downstream deposits containing gravel-supported blocks that show evidence of percussion, but not rounding. In this report, the term *block* is used for a large, angular rock fragment, showing little or no modification by transporting agents, its surfaces resulting from breaking of the parent mass, and having a diameter greater than 10 in [256 mm].

The resulting landforms look like abandoned quarries - angular bedrock surfaces in closed depressions [Fig. 10]. I refer to these as *kolk pits*, or *kolk lakes* if they retain water, or, simply, *kolks.* Their long dimensions are often subparallel to strike of the steeply dipping metasedimentary rocks [Fig. 11], rather than aligned in the flow direction. Kolk pits and kolk lakes occur only in the sublake notches and are concentrated along the crests [see Fig. 9]. Surrounding the kolk pits are scabland areas, relatively smooth upcurrent of the notches and on the valley slopes above the notches, becoming progressively rougher near the kolk pits. Some of the smooth surfaces in the scoured areas and all of the smooth surfaces around the kolk pits are thin bedload gravels from terminal flood flows.

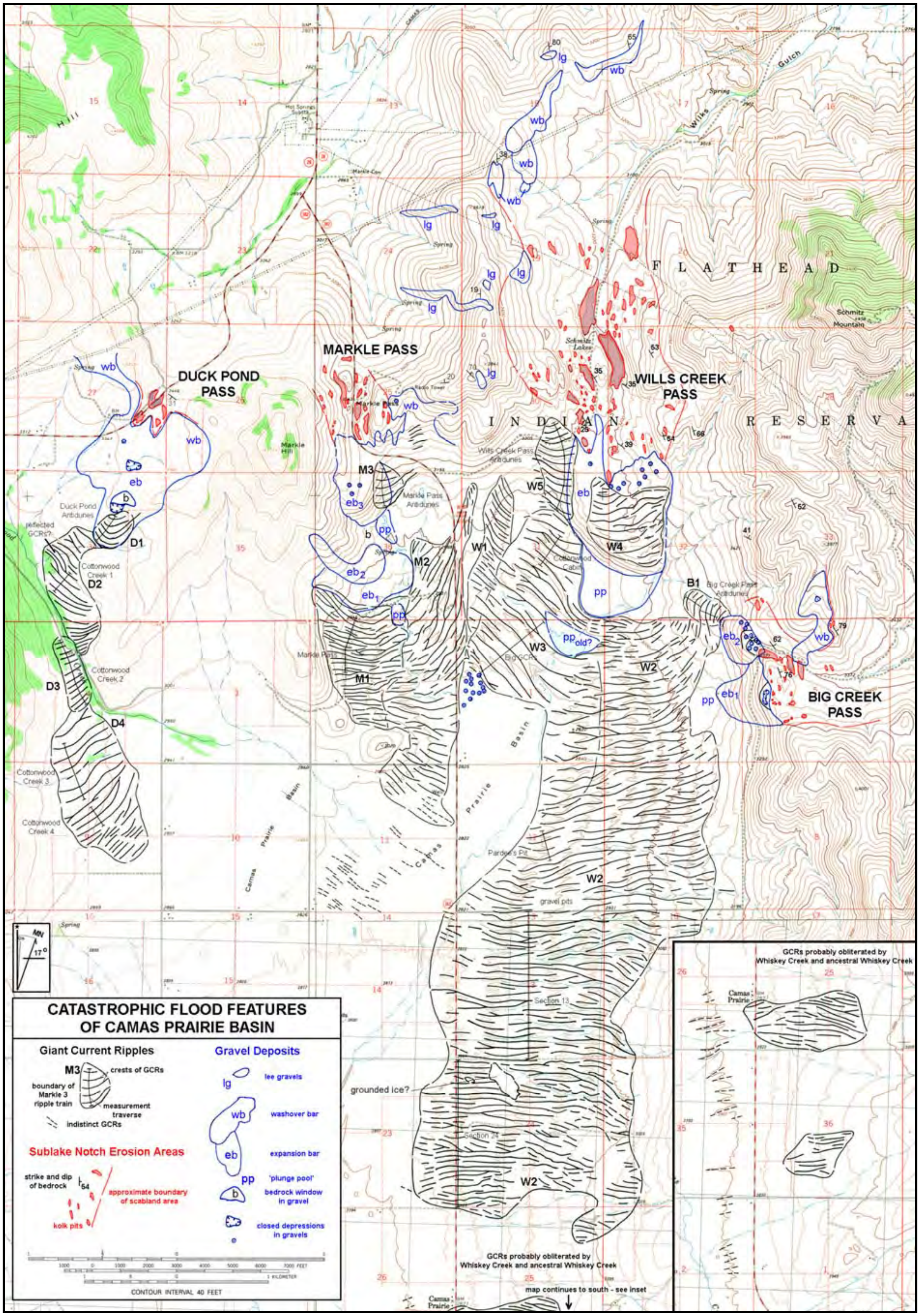

Figure 9—Catastrophic flood features of Camas Prairie Basin.

Figure 10—Kolk pit at Markle Pass.

Figure 11—Aerial view to the north of kolk pits in Big Creek Pass. Note alignment of kolk pits parallel to strike of bedrock and nearly perpendicular to current flow, which was to the left [west].

Bottom currents apparently had extremely high tractive forces because of the great depth and velocity of the flood flows. Bedload gravels, including cobble- and boulder-sized clasts, were blanket-like in their distribution and deposition, accumulating in thicker deposits where currents slacked. Flood gravels deposited in the lee of local topography are here mapped as *lee gravels*. Some lee gravels were deposited down-current from topographic barriers on surfaces that slope in the down-current direction; most were deposited down-current from barriers that occur on surfaces that slope in the *up-current* direction, indicating the gravels were transported upslope. Some of these gravels were deposited on the upslope sides of approaches to sublake notches, as shown in Figures 12 and 13 north of Markle Pass [Fig. 9 shows locations of lee gravels]. Similar lee gravels also occur locally within the sublake notches.

Figure 12—Lee gravels on the downcurrent – but upslope – side of a ridge north of Markle Pass. Current flowed from the left [north] up the slope to Markle Pass [out of view to the right].

Figure 13—Lee gravels of Figure 12.

Some unusual bars consist of gravels that were transported upslope and then dumped just over a sublake divide on the lee slope, referred to here as *washover bars* [Fig. 8]. Figure 9 shows the locations of these deposits, and Figure 14 is a photograph of washover bars. Figure 15 shows an exposure in a washover bar at Big Creek Pass with the gravel-bedrock contact. Small washover bars occur on several of the sublake notches.

Expansion bars, or *deltaic bars* of Pardee [1942], were deposited below and down current from each of the sublake notches [Figs. 8 and 9]. In some cases there are multiple bars. These landforms are generally steep-sided lobes, with a fairly flat top [Fig. 16], with or without secondary bedforms like giant current ripples and chute and pool structures. Pardee [1942, p. 1588] described the currents producing these expansion bars: *The initial direction and momentum of the descending masses of water plus increased specific gravity due to the fine sediment picked up on the way would tend to hold the currents to the bottom for a considerable distance.* Geologists today might say the same thing differently by describing inertia-dominated homopycnal flow that generated hyperpycnal turbidity currents. The bedload gravels are poorly sorted into crude foreset beds of open-work gravels [Fig. 17], and large blocks embedded in these expansion bars [Fig. 18] probably represent fallout from decaying kolk vortices.

Figure 14—Washover bars north of Wills Creek Pass. Current flowing from the right [north] transported gravels upslope to the ridge crest and deposited them on and just to the left of the sublake divide.

Figure 15—Bedload gravels of washover bar at Big Creek Pass on vertical metasedimentary rocks of Prichard Fm [E Mbr]. Current flow to left [west].

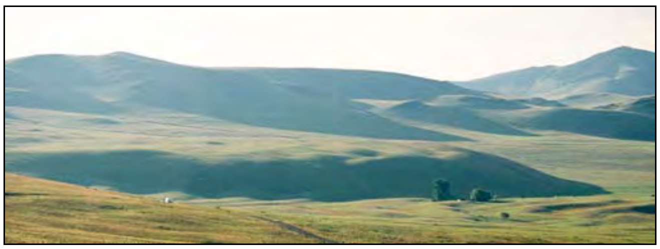

Figure 16—Expansion bar below Wills Creek Pass. Gravels in 200-foot high [60 m] bar were transported from the notch to the left of the photo.

Figure 17—Gravels in expansion bar below Big Creek Pass. Crude foreset beds dip 29^{o} to the west. Note open-work cobble-pebble gravel.

Figure 18—Block of metasedimentary rock suspended in expansion bar gravels below Rainbow Lake Pass.

Much of the Camas Prairie Basin is covered by a huge field of giant current ripples 8.3 miles [13.4 km] long and 2.7 miles [4.3 km] wide [refer to Fig. 9]. The ripple field is complex, being the combined result of four individual ripple fields, each emanating from one of the four sublake notches. The higher Duck Pond and Big Creek Passes were minor contributors, and Wills Creek Pass seemed to contribute more than Markle Pass.

Giant current ripples consist of three different types of dunes: *normal dunes*, *reverse dunes*, and *antidunes*. Normal dunes are long, two-dimensional dunes with shorter lee sides, and therefore steeper lee slopes, and they are the most common type of dune at Camas Prairie. Reverse dunes are similar to normal dunes, except they have shorter stoss sides. Reverse dunes were recognized only below Duck Pond Pass, but they may well occur in other areas. Antidunes are short, arcuate three-dimensional dunes with shorter stoss sides. They occur in only four small ripple trains, one below each sublake notch along or at the end of an expansion bar on a steep slope.

Wills Creek Pass Sublake Notch System

Most of the initial flow from the Little Bitterroot Valley came south into the Camas Prairie Basin over the north basin rim, a sublake divide that runs between Schmitz Mountain on the east and Markle Hill on the west [Fig. 9]. A ridge [unnamed on topo map] in the middle of this divide that extends north and then east separated flow into the Wills Creek notch on the east and the Markle Pass notch on the west. Wills Creek Pass is the largest and lowest of the sublake notches, thus it carried the last of the flood flow into the Camas Prairie Basin and exhibits flood features larger and more extensive than those in the other three notches [Fig. 19].

Figure 19–Aerial view to the east of Wills Creek Pass system. ad, antidunes; eb, expansion bar; k, kolk pits; p, pool; pp, 'plunge pool'; rc, rip channel; w1-w5, Wills Creek Pass ripple trains 1 to 5.

Flood currents concentrated in the Wills Creek sublake notch ripped out huge volumes of bedrock and created a sharp notch about 7000 ft [2100m] long, 5000 ft [1500 m] wide, and as much as 200 ft [60 m] deep [Fig. 9, Fig. 20]. A series of transverse profiles across the notch indicates an average cross-sectional area of about 450 thousand ft^2 [42 thousand m^2], which yields a rough estimate of 2.6 billion ft^3 [74 million m^3] of bedrock that were excavated. This excavation must have taken place over a matter of hours, or at most, a few days, thus a rough approximation of the erosion rate would be as much as 100 ft/day [30 m/day] or one billion cubic feet [30 million cubic meters] of bedrock per day! Even if one invokes some ten catastrophic Missoula floods to excavate the notch and thus reduces the rate by an order of magnitude, the erosion rate would still be 10 ft/day [3 m/day] or 100 million cubic feet [3 million cubic meters] of bedrock per day – an aqueous erosion rate difficult to comprehend.

Upcurrent from the notch the ground surface appears fluted [Fig. 21]. Bedrock is exposed at the surface or is covered by a thin veneer of bedload gravel. Closer to the crest of the notch the surface gets rougher, and well defined *rip channels* appear; these are analogous to scour channels, but they definitely are not caused by scour, but by kolk plucking.

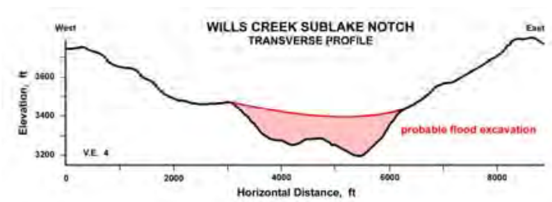

Figure 20—Transverse profile across Wills Creek sublake notch showing suggested flood excavation.

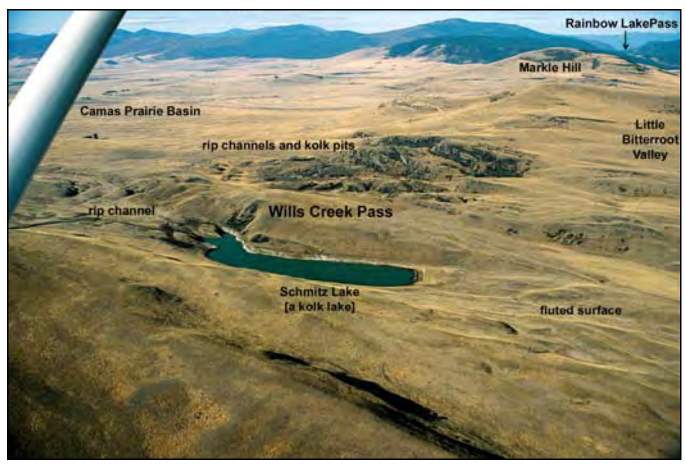

Figure 21–Aerial view to west of Wills Creek Pass sublake notch on north rim of Camas Prairie Basin.

Ubiquitous evidence of kolk plucking can be observed in the field, and small kolk pits are too numerous to count. The 71 kolk pits shown in Figure 9 are only those that form closed depressions and are large enough to be mapped on air photos. Four of the kolk pits are longer than 1000 ft [300 m], and Schmitz Lake is about 1850 ft long by 380 ft wide [560 m by 120 m][Fig. 21]; it occupies the bottom of a rip channel and has a depth below the channel of more than 60 ft [18 m]. Kolk pits are generally elongate subparallel to strike of the metasedimentary rocks, which here is also subparallel to current flow.

Several occurrences of lee gravels can be recognized north of Wills Creek Pass along the ridge between Wills Creek Pass and Markle Pass. One pocket of lee gravels was clearly transported upslope [northernmost part of Fig. 9]. Washover bars, consisting of scalloped tongues of gravel that were transported upslope, lie on the downcurrent side of this same sublake divide, which is nearly normal to current flow [Figs. 9, 14].

The Wills Creek expansion bar is the largest at Camas Prairie, and it exhibits all of the features in these bars. It is about 4300 ft [1300 m] long, 3600 ft [1100 m] wide, and 200 ft [60 m] high [Figs. 9, 16, Figs. 22, 23]. The proximal surface of the bar is graded to the notch bedrock surface at the lower kolk pits, even continuing to maintain the valley cross-section profile a short distance downcurrent [best seen using the stereogram in Fig. 22]. The modern divide is at the contact of the scabland area and the bar. A pronounced depression reminiscent of a plunge pool lies at the foot of the bar; it is broad and flat with a very sharp boundary with the bar. Possible chute and pool bedforms occur near the proximal end of the bar, and giant current ripples cover most of the bar. Sediments in the bar appear to be open-work boulder-cobble-pebble gravel, with little matrix, but there are no good excavations in this bar. Blocks are numerous, especially on the proximal medial surface immediately downcurrent from large kolk pits. Blocks along the sides of the expansion bar appear to be floating in the gravels, probably as a result of dropping from kolk suspension into the main bedload gravels.

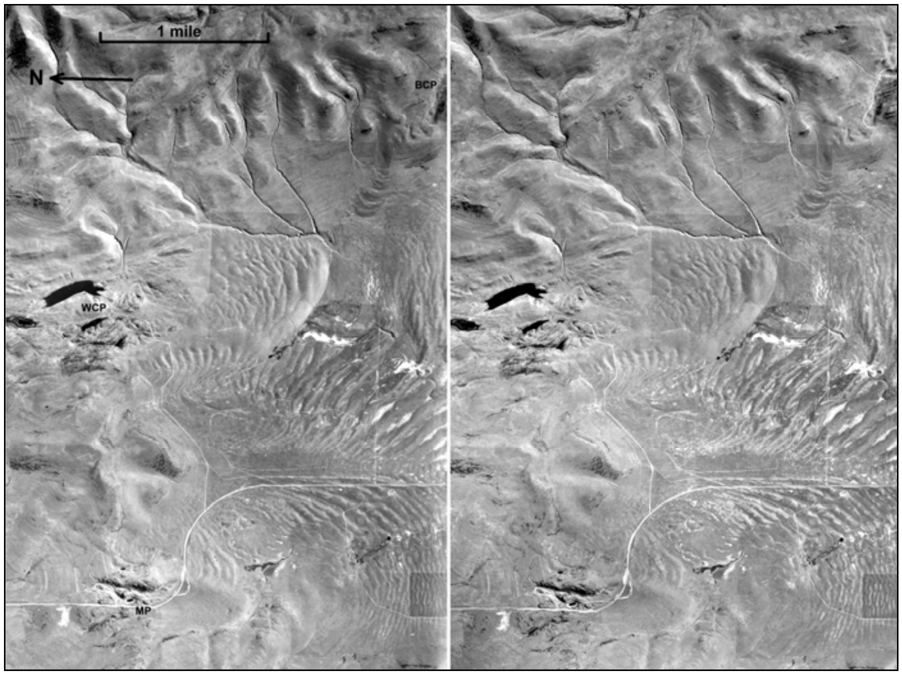

Figure 22—Stereogram of the northeastern part of the Camas Prairie Basin, showing three of the inlet sublake notch systems: Markle Pass [MP], Wills Creek Pass [WCP], and Big Creek Pass [BCP].

A series of longitudinal profiles through the Wills Creek Pass sublake notch was used to estimate the third dimension, and, therefore, the volume of the material deposited in this expansion bar. This rough calculation yields an estimated volume of 2.1 billion ft^3 [59 million m^3] of gravel. A comparison with the estimated volume of rock excavated from the Wills Creek notch indicates that about 80% of the excavated rock was deposited in the expansion bar. Once again considering rates, as was done above for erosion, one arrives at the phenomenal rate of deposition of 100 million cubic feet per day [3 million cubic meters per day]. Given the very rough approximation used, one must still wonder if similar aqueous deposition rates have been seen elsewhere.

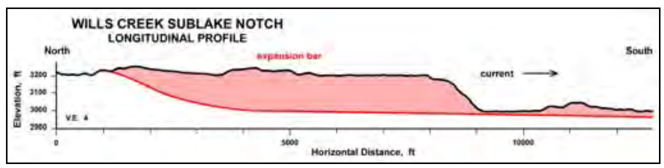

Figure 23—Longitudinal profile through Wills Creek sublake notch. Red-shaded area is the suggested deposition of gravels.

The giant current ripples below Wills Creek Pass are the largest and most extensive in the basin. Five distinct ripple trains are recognized, four of which contain normal dunes. A narrow train of arcuate antidunes runs alongside the expansion bar [Fig. 24]. These are discussed in the section below on giant current ripples.


Figure 24—Antidunes viewed in the downcurrent direction [to south]. Expansion bar to the left. Normal giant current ripples beyond cottonwood trees.

Markle Pass Sublake Notch System

The Markle Pass sublake notch is the second largest and second lowest of the four sublake notches [Fig. 9, Fig. 25]. Like the Wills Creek Pass sublake notch, flood flow came from the Little Bitterroot Valley to the north, but the currents here were restricted to a narrower notch and tore out only three rip channels. An estimate of bedrock excavated by the floods is shown in the photo in Figure 26 and the transverse profile of Figure 27.

Kolk pits are easily observed, because Montana Highway 382 passes through them, in fact, alongside the deepest kolk pit, which is 76 ft [23 m] below the highway and 187 ft [57 m] below the rock ledge immediately to the east. 21 kolk pits are mapped, the longest about 1500 ft, and all are less than about 200 ft wide. All are subparallel to strike of the bedrock.

Lee gravels are well displayed along two arcuate ridges north of Markle Pass, as discussed previously, and a small washover bar was deposited just east of Markle Pass. A well developed expansion bar grades to the floor of the notch [Figs. 28 and 29]. This lobate bar is flat-topped and steep-sided like the Wills Creek expansion bar, but lacks the giant current

Figure 25–Aerial view to north of Markle Pass inlet sublake notch system. ad, antidunes; eb, expansion bar; lg, lee gravels; p, pool; pp, 'plunge pool'; M1, M2, Markle Pass ripple trains 1, 2.

ripples on top, although it does have three closed depressions that may be chute and pool structures. A broad flat area along the base of the expansion bar is similar to a plunge pool. Two other gravel bars farther downcurrent probably represent other, smaller, expansion bars, the most distal of which has its own 'plunge pool'.

Two trains of normal giant current ripples extend southward below Markle Pass, and a narrow train of arcuate antidunes runs alongside the expansion bar. These are discussed below.

Figure 26—View to south of Markle Pass sublake notch from the Hot Springs airstrip in Little Bitterroot Valley. Flood currents tore through the notch into the Camas Prairie Basin.

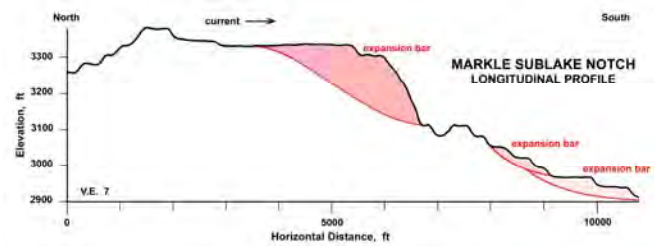

Figure 28— Longitudinal profile through Markle Pass sublake notch. Red-shaded areas are the suggested deposition of gravels.

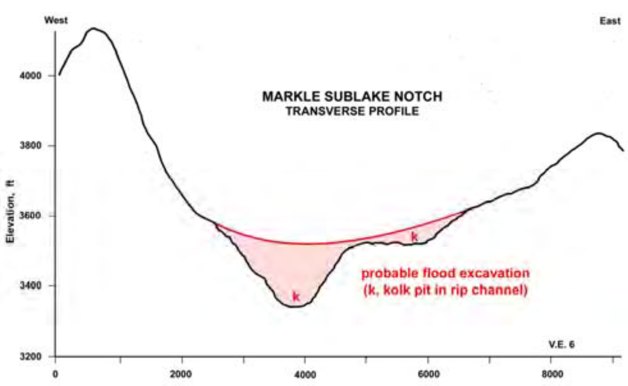

Figure 27—Transverse profile across Markle Pass sublake notch.

Figure 29—Expansion bar below Markle Pass has a flat top and steep sides. Markle Pass to right; giant current ripples alongside the expansion bar are antidunes, giant current ripples in foreground are normal dunes.

Big Creek Pass Sublake Notch System

Flood flow through the Big Creek Pass sublake notch came from the lower Little Bitterroot Valley and the Mission Valley to the east and was the second sublake notch to be abandoned [Fig. 30]. Erosion in the notch was relatively minor; nonetheless, 24 kolk pits were mapped, all of which are elongate subparallel to strike of bedrock and almost normal to the flood current [Figs. 9 and 11].

The notch crest to the north of the pass has two high kolk pits, below which is a washover bar with several closed depressions in the gravels that suggest chute and pool bedforms. Several large blocks litter the surface of the washover bar, the largest of which is shown in Figure 31 [b in Fig. 30]. This large block has split in place; when reconstructed, the dimensions are 20.1 ft x 10.6 ft x 8.9 ft [6.1 m x 3.2 m x 2.7 m], with a volume of about 1900 ft^3 [53 m^3] and a weight of about 160 tons [145 tonnes]. It apparently was lifted and transported about 420 ft [128 m] in a S79W direction from its kolk pit.

Figure 30–Aerial view to the northeast of Big Creek Pass system. b, block; eb, expansion bar; k, kolk pits; p, pool; pp, 'plunge pool'; rc, rip channels; wb, washover bar.

Two expansion bars extend from the notch [Fig. 9, Fig. 30]. The lower expansion bar is lobate, with a surface covered with numerous closed depressions, or pools [Fig. 32]. These are suggestive of chute and pool bedforms, but no gravel exposures occur in any of them, so the high-angle backsets expected in chute and pool structures cannot be documented. The open-work boulder-cobble-pebble gravels are difficult to excavate, but in one small pit, flat cobbles do dip in the upcurrent direction, averaging 25° [Fig. 33]. This is consistent with, but not evidence for, steep backset bedding, because imbrication cannot be discounted. It is clear, however, that these bedforms were created by very high velocity currents.

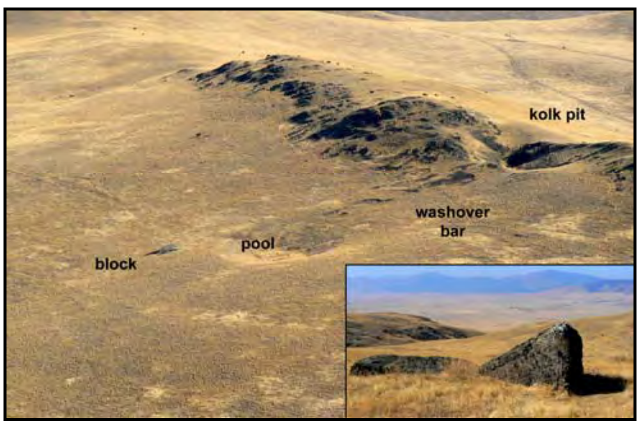

Figure 31— View northeast of washover bar at Big Creek Pass. The 160-ton block was plucked from kolk pit at right and transported 420 ft by kolk action. Inset shows the block [split in place], pole is 4 ft [120 cm] long.

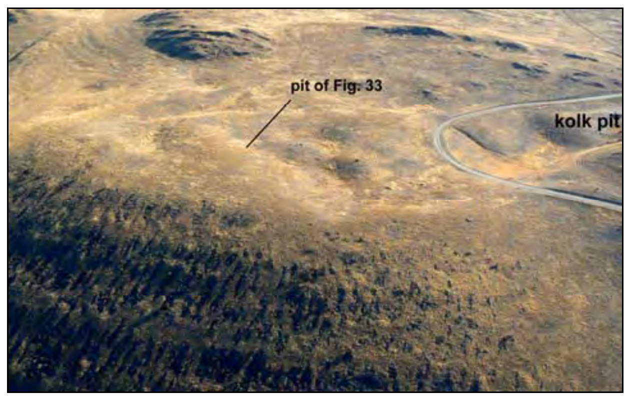

Figure 32— Ten pools are visible in the gravels of the lower expansion bar at Big Creek Pass.

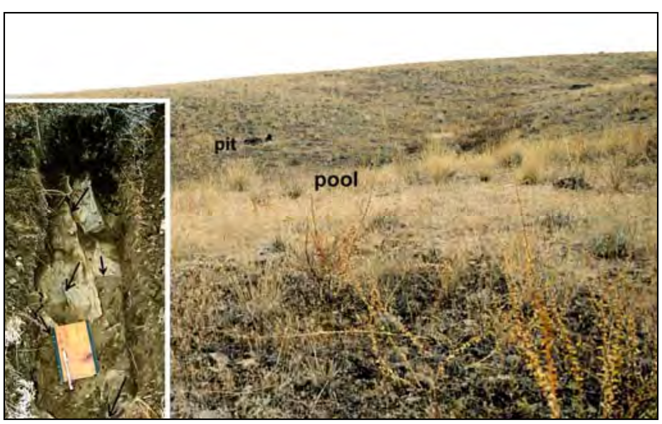

Figure 33— Chute and pool bedform on Big Creek expansion bar [Fig. 32 shows location]. Shallow pit [inset] in upcurrent-facing surface below pool shows clasts dipping steeply back into pool, dip indicated by arrows.

The lower expansion bar grades to the floor of the notch [Fig. 34]. The higher, and presumably older, bar is broad and short, with a large 'plunge pool' at its base. Along the proximal edge are closed depressions suggesting chute and pool bedforms.

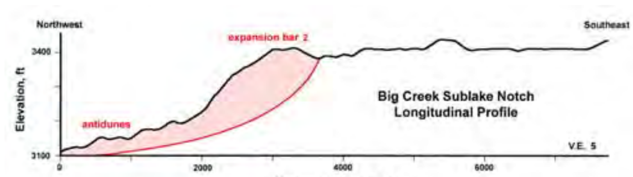

Figure 34— Longitudinal profile through Big Creek Pass sublake notch. Red-shaded area is the suggested gravel deposition.

Although gravels from the Big Creek sublake notch probably contributed to the giant current ripples on the floor of the basin, only one train of giant current ripples clearly emanates from the Big Creek notch. This is a train of five antidunes that lies along the lateral distal edge of the lower expansion bar [Figs. 22 and 34].

Duck Pond Pass Sublake Notch System
Flood waters from the Little Bitterroot Valley initially tore through Duck Pond Pass during the early flow through Rainbow Lake Pass. After the Rainbow Lake outlet was abandoned, flow turned south, but the current traveled less than two miles before hitting a transverse mountainside that deflected flow to the southeast along Cottonwood Creek [Fig. 35]. This is the highest of the Camas Prairie inflow sublake notches and thus the first to be abandoned.

Although considerable erosion may have taken place during early flows, only a small scabland notch is recognized [see Fig 9]. Three narrow rip channels contain four kolk pits, two of which contain the actual duck ponds.

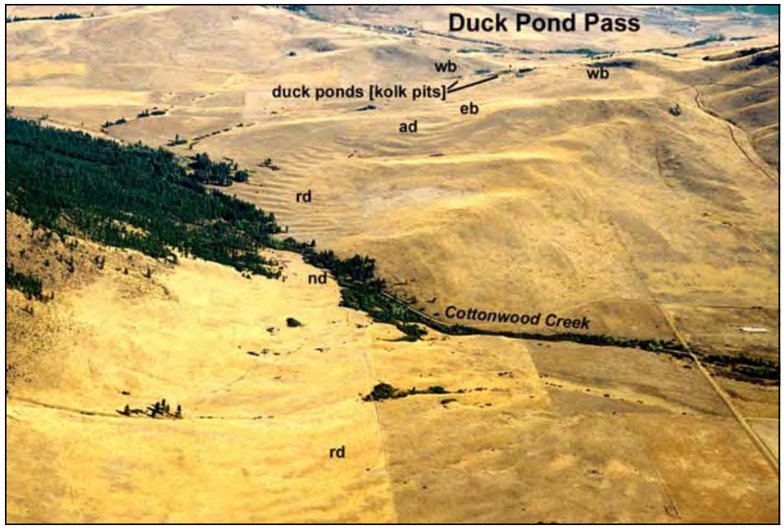

Figure 35–-Aerial view to the north of Duck Pond Pass system. ad, antidunes; eb, expansion bar; nd, normal dunes; rd, reverse dunes; wb, washover bar.

Washover bars on either side of the notch merge with the expansion bar, which is less distinct than expansion bars below the other sublake notches. The expansion bar is more like an apron of relatively thin gravel spread out on a gentle slope, with some bedrock exposed through the gravels [Fig. 36]. The expansion bar appears to be a composite of at least two separate flood flows, each with a distinct train of blocks. On the surface of the bar are several small, shallow closed depressions and one quite large one in the center, perhaps the pools of chute and pool bedforms.

Giant current ripples below Duck Pond Pass change character distally, from antidunes on the end of the expansion bar to reverse dunes, to normal dunes along the low-gradient Cottonwood Creek, back to reverse dunes on steeper slopes at the end of the ripple field.

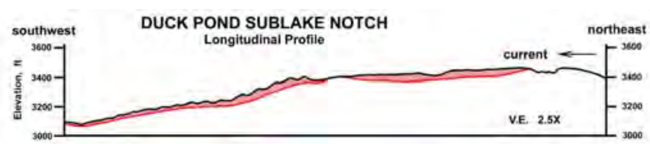

Figure 36— Longitudinal profile through Duck Pond sublake notch. Red-shaded area is the suggested gravel deposition.

A higher, minor sublake notch occurs about 2 mi [3 km] north-northwest of Duck Pond Pass on the west side of Burke Hill at 3991 ft elevation [northernmost current arrow on Fig. 3]. The notch shows no significant erosion, but it contains minor flood gravels.

CAMAS PRAIRIE FLOOD OUTLETS

Rainbow Lake Outlet System
When Lake Missoula's dam failed, water from Camas Prairie, Little Bitterroot Valley, and Mission Valley poured directly toward Eddy Narrows through Rainbow Lake Pass [see Fig. 3]. The pass was under about 300 ft [90 m] of water initially, but flood waters eventually tore out about 360 ft [110 m] more of competent bedrock, primarily by kolk action. Flood currents carved a long, remarkably flat rip channel in very competent bedrock, the western part of which was buried by flood gravels [Fig 37]. Direct flow to Eddy Narrows was impeded by Locust Hill, a wedge-shaped bedrock hill that split the flood currents into northwest and southwest components [Fig. 38].

The interpretation of this outlet system is based on photo interpretation and field checks, limited to observation of landforms and surface deposits. The system is a fine example of flood outlet geology, and a detailed stratigraphic study of the depositional system is warranted.

Pre-flood Topography Rainbow Lake *Pass* today is not visible, either in the field or on the topographic map. It is labeled on the topographic map about 1000 ft west of Rainbow Lake, but in reality there are two Rainbow Lake *Passes*, one in the Camas Creek drainage 2000-5000 ft [600 - 1500 m] southeast of the lake at an elevation of 3640-3680 ft and a second in Toolman Slough 3000-10 000 ft [900 – 3000 m] northeast of the lake at an elevation of 3600-3640 ft; surveying equipment would be required to define either one. Interpretation of drainage patterns above the rip walls, however, suggests the preflood divide passed through what is today the western part of Rainbow Lake. A topographic profile at this location indicates about 360 ft [110 m] of flood erosion occurred, putting the preflood pass at an elevation of about 3950 ft.

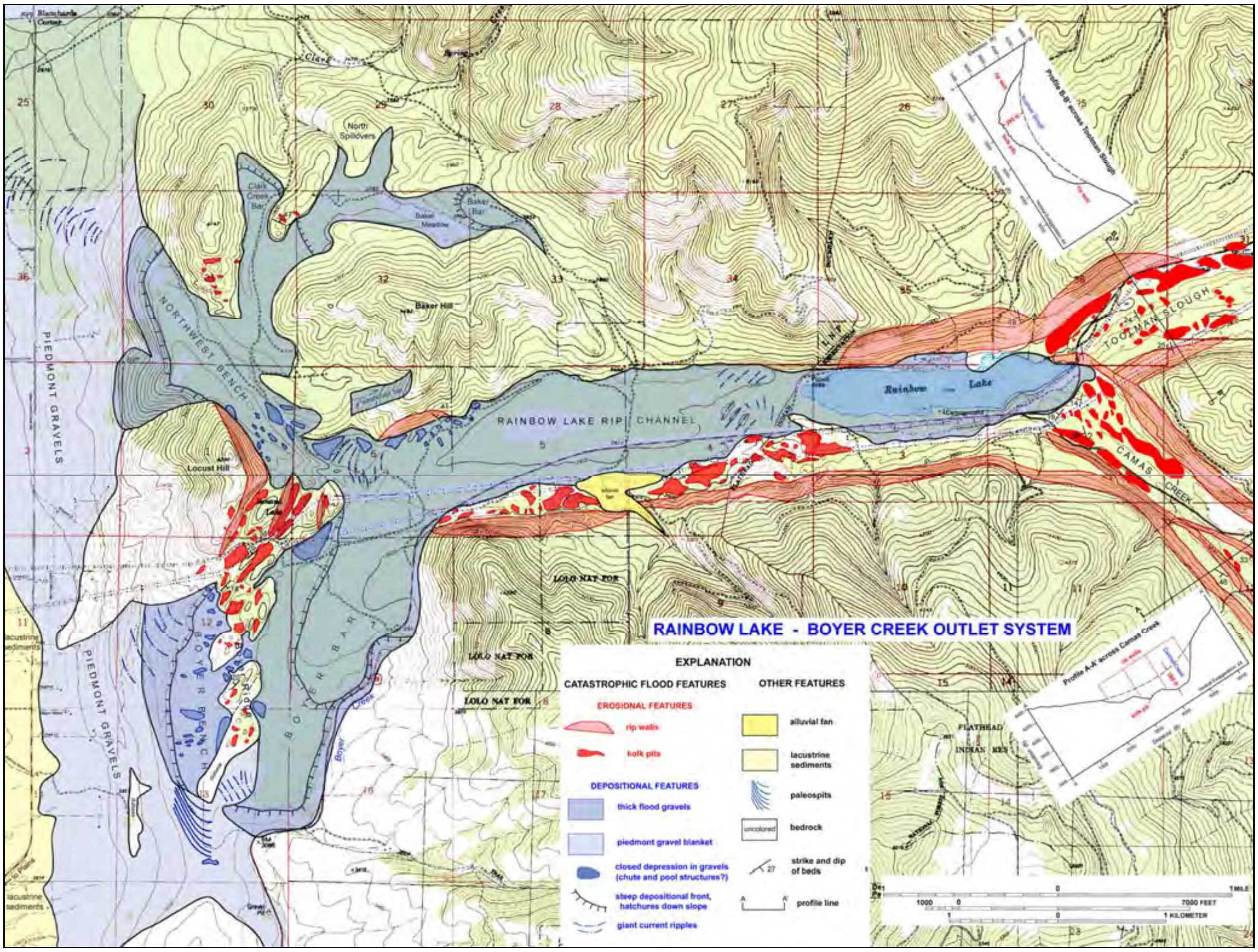

Figure 37—Catastrophic flood features of the Rainbow Lake outlet system [scale approximately 1:65,000].

Flood Erosion Flood currents from the east flowed around an unnamed hill east of Rainbow Lake and converged at Rainbow Lake [see Figs. 3 and 38, Fig. 39]. Kolk action gouged out two nearly horizontal rip channels, Camas Creek rip channel to the south and Toolman Slough rip channel to the north, both cut in argillites, siltites, and metaquartzites of the Upper Prichard Fm.

The Camas Creek rip channel is about 9000 ft [2750 m] long, about 3000 ft [900 m] wide at the top of the rip walls, and about 1500 ft [450 m] wide along the floor. Projection of topography above the rip walls suggests 260 ft [80 m] of erosion [see Fig. 37, profile A-A’]. Three separate rip walls are recognized on the left wall, with two bedrock benches between them, and one continuous rip wall on the right. Numerous kolk pits line the channel bottom; 22 of them are large enough to be mapped, up to 2300 ft [700 m] long and 400 ft [120 m] wide. Most are subparallel to the northwest strike of the bedrock, which was also the current direction.

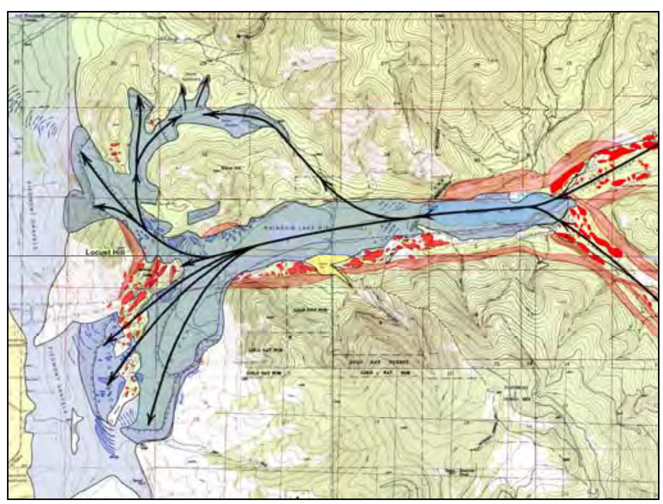

Figure 38—Main currents in the Rainbow Lake outlet system. Currents from Toolman Slough and Camas Creek converged at Rainbow Lake to form the main outlet current in the Rainbow Lake rip channel. Locust Hill split this current into northwest and southwest components.

The Toolman Slough rip channel is about 10 000 ft [3000 m] long, about 4000 ft [1200 m] wide at the top of the rip walls, and about 1000 ft [300 m] wide along the floor. Projection of topography above the rip walls suggests 280 ft [85 m] of erosion [see Fig. 37, profile B-B']. One continuous rip wall is on the north, while to the south an upper rip wall is separated from the channel floor by a bedrock bench and a lower, steep slope. 32 mapped kolk pits are up to 2700 ft [800 m] long and 500 ft [150 m] wide. Small kolk pits tend to be elongate parallel to the northwest strike or diamond-shaped, but the largest kolk pits are more parallel to flow direction. The Toolman Slough rip channel obliterated the preflood interfluve that existed between the headwaters of Camas Creek and Cottonwood Creek.

Figure 39—View east of Toolman Slough and Camas Creek rip channels converging at Rainbow Lake; rw, rip wall.

Rainbow Lake was plucked from Upper Prichard Fm metasedimentary rocks by kolk vortices where the flood currents from Camas Creek and Toolman Slough converged [Fig. 40]. A Camas Creek rip wall truncates the south rip wall and bench of Toolman Slough [see Figs. 37 and 39], suggesting the Camas Creek current was more aggressive. Rainbow Lake is 7400 ft [2250 m] long and 1300 ft [400 m] wide [at 3485 ft elevation]. Rip walls with hanging tributaries on either side of the lake extend up to 4000 ft elevation, above which the topography can be projected to indicate 360 ft [110 m] of erosion.


Figure 40—Bedrock plucked by kolk action at head of Rainbow Lake.

The Rainbow Lake rip channel extends west from Rainbow Lake to Locust Hill. It is about 23 000 ft [7000 m] long, about 4500 ft [1400 m] wide at the top of the rip walls, and about 3000 ft [900 m] wide along the floor, cut mostly into Upper Prichard Formation metasedimentary rocks. Rip walls are continuous along the south side, less so on the north [see Fig. 37]. Most of the channel floor is now covered by flood gravels, but along the foot of the south rip wall where bedrock is exposed, 30 kolk pits are mapped, up to 1500 ft long and 700 ft wide [450 x 200 m]. Together with the rip channel in Toolman Slough, the flood tore out a remarkably long, flat rip channel that, over a distance of 30 000 ft [9000 m], varies less than 40 ft [12 m] from an elevation of 3600 ft.

Locust Hill, a bedrock hill of Lower Prichard Formation metasedimentary rocks, stood as an obstacle at the end of the Rainbow Lake rip channel and thus bore the full brunt of the flood currents [Fig. 41]. A severe whamout on the upcurrent side of the hill is marked by a vertical series of three rip walls with basal kolk pits, some of impressive depth [Fig. 42]. Banana Lake is in a kolk pit more than 80 ft [24 m] deep, 2200 ft [670 m] long and a few hundred ft wide, at the foot of a

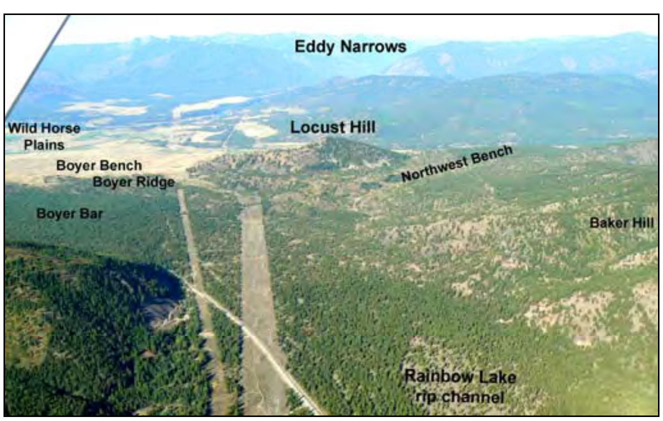

Figure 41—View west down Rainbow Lake rip channel to Locust Hill, with Eddy Narrows in the background. Flood currents split around Locust Hill.

Figure 42—View west of Locust Hill whamout. At the base of each rip wall, out of view, are arcuate kolk lakes, including Banana Lake below the middle rip wall.

rip wall about 170 ft [50 m] high. Its convex shape wraps around the nose of Locust Hill, analogous to a scour pit on the upstream side of a stream boulder. Kolk pits at an elevation as high as 3900 ft attest to the piled up water as flood currents surged around, and perhaps over, Locust Hill.

Floodwaters diverted to the northwest by Locust Hill cut a rip channel between Locust Hill and Baker Hill, now filled with flood gravels. Boyer Ridge, a southward extension of Locust Hill, is a bedrock ridge of metasedimentary rocks and mafic sills; flood currents deflected to the southwest by Locust Hill scoured the ridge and plucked 21 mapped kolk pits up to 600 ft long, 300 ft wide, and 30 ft deep [180 x 90 x 10 m] [Fig. 43].

Flood Deposition A broad gravel plain covers most of the Rainbow Lake rip channel floor, slightly higher in the center. Flood gravels in a shallow pit a few thousand feet west of Rainbow Lake are boulder-cobble-pebble gravel, round-to-angular mostly subangular, with open-work texture and maximum boulder size of 9 ft [3 m][Fig. 44]. Near the west end of Rainbow Lake are a few ridges 8-12 ft [2.5 – 3.5 m] high that probably are giant current ripples. Toward the west end of the rip channel, a trough developed in the flood gravels along the north wall in which the gravel surface is hummocky with numerous closed depressions that may represent chute and pool structures. Just before climbing up into the Locust Hill-Baker Hill rip channel, the trough reaches a nadir in which closely spaced giant current ripples reach heights of 40-50 ft [12-15 m].

Figure 43—View to northeast of Boyer Ridge, where floodwaters plucked numerous kolk pits in bedrock. Boyer Bench in foreground shows several closed depressions in flood gravels.

Figure 44—Flood gravels in Rainbow Lake rip channel. Pick handle is 16½ in long [42 cm].

Flood currents surged to the northwest out of the Rainbow Lake rip channel up an unnamed drainage east of Baker Hill in Section 33 [see Fig. 38]. No flood deposits remain in the drainage, possibly because of later back drainage, but a few flood boulders can be found just below the head of the drainage, including a 5-ft [1.5 m] stromatolite boulder. North of the divide, flood gravels accumulated in an expansion bar built out into Baker Meadow [see Fig. 37]. The Baker bar, built of a heterogeneous cobble-pebble gravel, has a broad, flat top and steep sides, with a steep, 50 ft [15 m] high, west-facing depositional front.

Flood currents also tore around the west side of Baker Hill from the Locust Hill – Baker Hill rip channel, carrying gravels northward to build an expansion bar in the upper headwaters of Clark Creek [see Fig. 37]. These currents apparently also curved around the north side of Baker Hill to the east, as indicated by a steep, 15-25 ft [5-8 m] high, east-facing depositional front in Baker Meadow. This current converged with the west-flowing current that built Baker bar, and together the currents carried flood gravels north that spilled into other tributaries of Clark Creek. These gravels are pebble-size, rounded to well rounded.

The northwest rip channel between Locust Hill and Baker Hill is filled with flood gravels with 16 mapped closed depressions. These may represent chute and pool structures, or they may be thin gravels filling kolk pits in bedrock. The gravels continue up and out onto the broad, flat surface of Northwest Bench, which appears to be a thick expansion bar [Fig. 45]. Thickness is unknown, but the steep, west-facing depositional front is 200–400 ft [60-120 m] high. Northwest Bench is about 200 ft [60 m] higher than the Rainbow Lake rip channel.

Boyer Bench [Fig. 46] is also higher than the gravels of Rainbow Lake rip channel, although slightly lower than Northwest Bench. The fairly flat surface is marked by 21 mapped closed depressions in the flood gravels, up to 1100 ft long, 250 ft wide, and 10 ft deep [330 x 75 x 3 m]. The steep, west-facing depositional front is about 200 ft high. Constituent gravels are exposed in two roadcuts that reveal up to 17 ft [5 m] of open-work boulder-cobble-pebble gravel that is angular to well rounded, mostly subrounded. A train of giant current ripples [GCRs] at the north end of the steep depositional front trends S40W and consists of five simple arcuate GCRs, the upper four of which were measured and are shown in Figure 47. The highest GCR is normal, whereas the others are antidunes. Median values are: wavelength, 564 ft [172 m]; height, 16 ft [5 m]; ripple index, 40; asymmetry [of the three antidunes], 0.62.

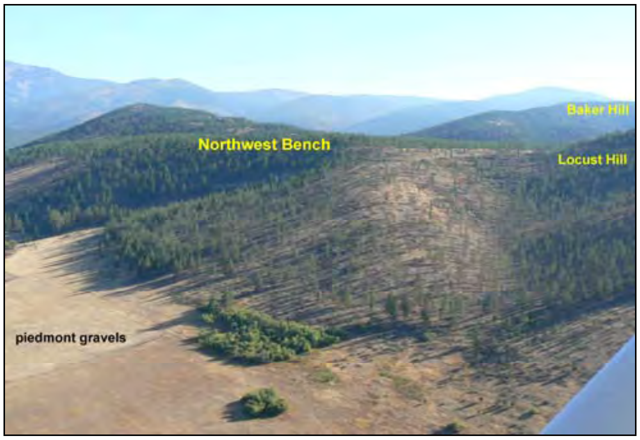

Figure 45—View northeast of steep depositional front of the Northwest Bench expansion bar. Flood current came from between Baker Hill and Locust Hill. Shorelines visible on piedmont gravels.

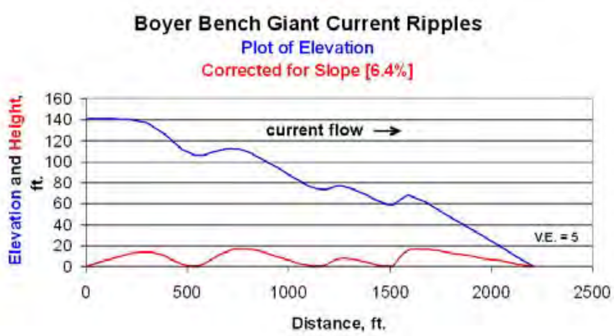

Figure 47—Giant current ripples on Boyer Bench depositional front.

Figure 49—View northeast of the steep front of Boyer expansion bar. Roadcut exposes crude foresets and suspended kolk-derived blocks [inset].

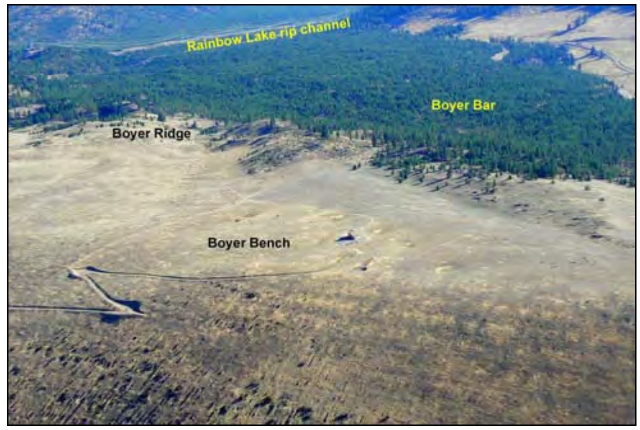

Figure 46—View northeast of flood gravels on Boyer Bench with numerous closed depressions [chute and pool structures?]. Steep depositional front marked by shorelines of Lake Missoula. Bedrock of Boyer Ridge separates Boyer Bench from the lower [treed] Boyer Bar.

The Boyer bar [Fig. 48] is a huge expansion bar in the upper reaches of Boyer Creek that contains most of the flood gravel load from the Rainbow Lake rip channel. The bar is 11 000 ft [3000 m] long and 2000-4000 ft [600-1200 m] wide. Thickness is unknown, but it is about 360 ft [110 m] at the distal end [Fig. 49]. Constituents are boulder-cobble-pebble gravel with open-work structure, with some very large boulders suspended in finer matrix. Road cuts in the depositional front show crude foreset bedding [Fig. 49, inset].

Figure 48—View northwest of the Boyer expansion bar filling Boyer Creek drainage from the end of the Rainbow Lake rip channel to its depositional front at the extreme left of photo.

Boyer bar shows two different surface levels, but it is unclear if they represent two different depositional events or if flood currents varied as a function of proximity to the Boyer Ridge, where the surface is lower and the currents presumably stronger; the latter seems more probable. Similarly, the surface of Boyer bar is lower than the surfaces on the two gravel benches, and this probably also represents response to paleotopography rather than different ages for the deposits.

Piedmont gravels are mapped where flood gravels blanket the surface but depositional landforms are lacking and bedrock exposures indicate the gravels are thin. Such flood gravels cover the lower slopes west of, and below, the gravel benches [see Fig. 37]. The piedmont gravel surfaces are generally featureless except for three small areas. Below the Northwest

Bench a train of simple arcuate giant current ripples trends N55W. About 20 dunes have an average wavelength of about 240 ft [73 m], a height of less than 4 ft [120 cm], and a ripple index greater than 60. A second train of linear giant current ripples trends S40W on a steep slope that climbs from the south end of Boyer bar *up* to Boyer Ridge [Fig. 50].

The piedmont flood gravels preserve numerous shorelines from late stages of glacial Lake Missoula. Below the south end of Boyer Bench the shorelines extend into a series of seven curved ridges that wrap around the end of Boyer Ridge [Fig. 51]. These low ridges, at 3300-3400 ft elevation, are paleospits built by south-flowing longshore currents in Lake Missoula.

Figure 50—View northeast of giant current ripples climbing up the slope from the treed Boyer bar to the diabase bedrock exposed on Boyer Ridge.


Figure 51—Lake Missoula shoreline features at south end of Boyer Bench. View north of shorelines to left of fence and seven paleospits right of fence. Depositional front of Boyer expansion bar far right.

Perma Outlet System

Once the Rainbow Lake outlet was abandoned, the Perma outlet at the southern end of the Camas Prairie Basin became the sole outlet [see Fig. 4]. All floodwaters passing south through the Camas Prairie Basin, in seeking the most direct route to the breached dam site, flowed south over the Perma Ridge. The floodwaters crowded the right [west] bank, scoured it, and cut, and perhaps undercut, near-vertical walls and plucked the lake-bottom ridge into a kolked scabland ridge. As the lake drained, falling levels caused this erosion to progress down the ridge to the east, creating a series of down-to-the-east stepping rip channels, perhaps accelerating when the Rainbow Lake outlet was closed. The lowest rip channel was active when the last inflow sublake notch into the Camas Prairie Basin [Wills Creek Pass] closed, and the Camas Prairie Basin drained through this lowest rip channel only. Only waning flows would have passed down Camas Creek.

Perma Ridge This ridge is 24,000 ft [7300 m] long, trending east-northeast. It formed the sublake divide between Camas Prairie and the Flathead Valley [Fig. 52]. The ridge is breached by the former and present Camas Creek graded to the Flathead River, but this low defile was not a significant path for flood flows. Most of the flood flow passed west of Camas Creek over Perma Ridge, seeking the shortest path to the Pacific Ocean, and tore a series of five rip channels, each characterized by ripped bedrock walls and kolk pits [Fig. 53].

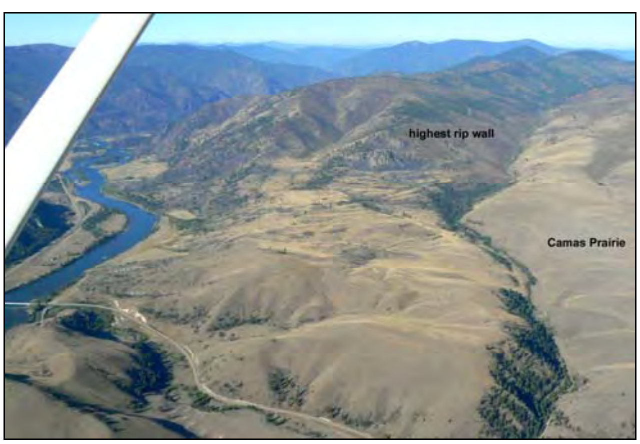

Figure 52—View west of Perma Ridge, Camas Creek in foreground by highway, bridge crosses Flathead River at Perma. Floodwaters from Camas Prairie tore over the ridge into the Flathead Valley, ripping out channels and kolk pits in the metasedimentary rocks.

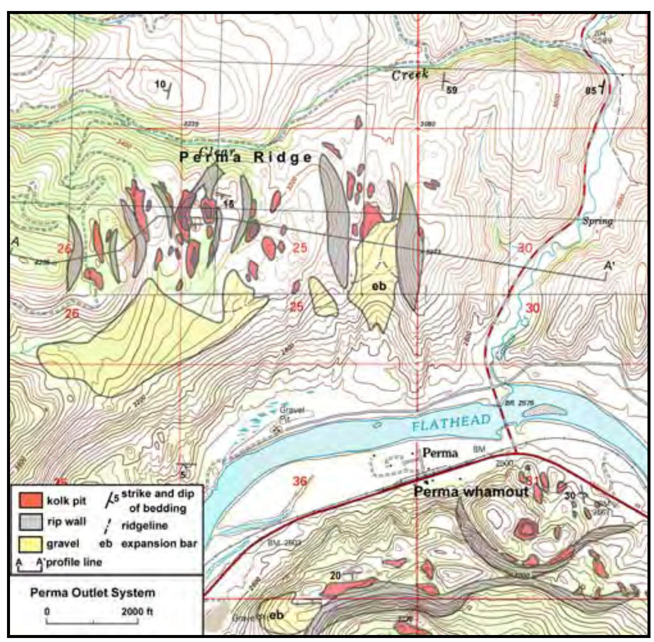

Figure 53—Flood features at Perma outlet system.

The five south-trending, stepped rip channels decrease in elevation from west to east, from about 3800 ft to about 3000 ft elevation [Fig. 54]. Each rip channel is bounded by bedrock walls, at least one of which shows evidence of plucking and is very steep [Fig 55]. In the four highest and westernmost rip channels, the higher, steeper wall is on the west side, whereas in the lowest rip channel the east wall is steeper. Each rip channel is floored by bedrock and contains kolk pits, some of which retain water [Fig. 56]. The number of mapped kolk pits in each rip channel ranges from three to eleven, but these are just the large, closed depressions that are mappable, and numerous open depressions and many smaller kolk pits exist.

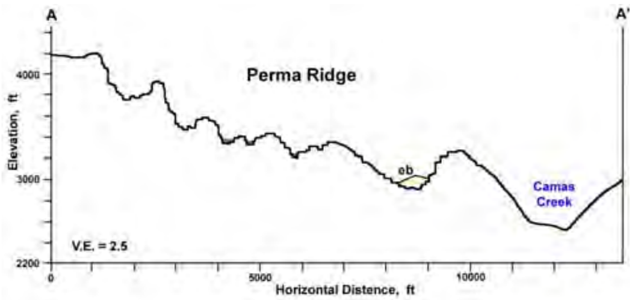

Figure 54—Profile of Perma Ridge looking north into Camas Prairie. Location of profile shown in Figure 53. eb, expansion bar.


Figure 55—View south of the upper two rip channels on the west end of Perma Ridge.

Below all the rip channels are minor flood gravels. A blanket of gravel is draped on the upper slope of the Flathead River Valley below the four higher, western rip channels; this could be subdivided, but with difficulty and uncertainty, into four expansion bars associated with each of the channels. The lowest rip channel on the east clearly has its own expansion bar, with a large closed depression in the proximal gravel that may be a chute and pool bedform [Fig. 57].


Figure 56—View south of kolk lakes in bottom of rip channels on Perma Ridge. Flathead River in distance.

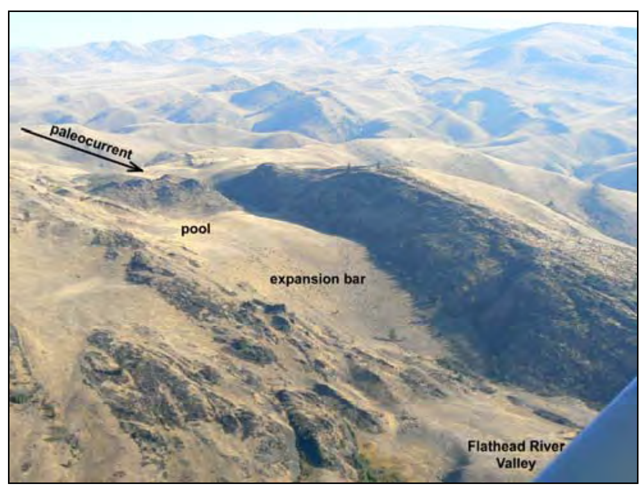

Figure 57—View northeast of the eastern, lowermost rip channel on Perma Ridge. Expansion bar at distal end of rip channel has a deep pool in the gravel.

Camas Creek cuts a small gorge through Perma Ridge but shows no evidence of flood features, neither erosion nor deposition. Its low gradient, along with the presence of lacustrine sediments in the lower reaches, would indicate it existed both before and after the major flooding.

Perma Whamout Area Opposite Perma Ridge on the south flank of the Flathead River Valley is a topographically anomalous area of severe erosion that probably resulted, at least in part, from the catastrophic flood discharge from the Camas Prairie Basin. The most obvious features of the Perma whamout are a lower, semicircular rip channel wall with a very deep, circular kolk lake in the middle, and a higher, long, rip channel wall with numerous kolks [see Fig. 53, Fig. 58].

The semicircular scabland basin, defined by a very steep, arcuate rip channel wall 100 to 150 ft [30-50 m] high, contains 14 kolk pits. In the lower part of the basin are eight kolk pits, each subparallel to strike. The large circular kolk lake in the center is more than 100 ft [30 m] deep [Fig. 59]. In the upper part of the basin, three elongate kolk lakes lie along, and aligned with, the foot of the rip wall. Between the arcuate scabland basin and the long, upper rip channel wall are 11 kolk pits that, where elongate, are subparallel to strike of the bedrock. The upper rip wall is more than 200 ft [60 m] high in places [Fig. 60], and above the upper rip wall air photos show two high kolk pits in what appear to be rip channels. The only flood deposit is an expansion bar below the distal end of the upper rip wall [Fig. 53].

Figure 58—View west of Perma whamout where Perma Bridge crosses the Flathead River.' lrw' marks ends of semicircular lower rip wall; 'urw', upper rip wall; k, deep, circular kolk lake.

Figure 59—View northwest of Perma whamout showing numerous kolk pits, some with water, both below and above the lower rip wall [lrw], seen only at far left because of perspective; upper rip wall [urw] similarly not visible.

GIANT CURRENT RIPPLES

It was clear to J.T. Pardee that his *giant ripple marks* or *ripple-mark ridges* were caused by unusual currents. In Victor Baker's [1973] classic study of the Washington scablands, he referred to similar bedforms as *giant current ripples*, the term used in this study. Giant current ripples [GCRs] formed transverse to the current and migrated downcurrent. They generally decrease in size to the south, although there are numerous exceptions. Crests are rather wide and rounded, making it sometimes difficult in the field to determine the actual crest, and away from the sublake notches they are asymmetrically steeper on the downcurrent [south] side. Heights generally are greatest near the centers of individual ripples and decrease toward the ends, with bifurcations common.


Figure 60—Distal [west] end of upper rip wall in photo center; wall is higher on skyline at left.

Most GCRs have two-dimensional, transverse, sinuous, in-phase shapes [usage of Allen, 1982, Fig. 61]. Following the recommendation of the SEPM Bedforms and Bedding Structures Research Group [Ashley, 1990], most of these bedforms would be classified as large to very large, two-dimensional, flow-transverse, subaqueous gravel dunes. Normal dunes, the most common in the basin, are two-dimensional with steeper lee slopes, and their shape is generally transverse sinuous in-phase. Reverse dunes have shapes similar to normal dunes, but have steeper stoss sides. Antidunes are three-dimensional, with short, arcuate transverse, convex-downcurrent shapes, with steeper stoss sides.

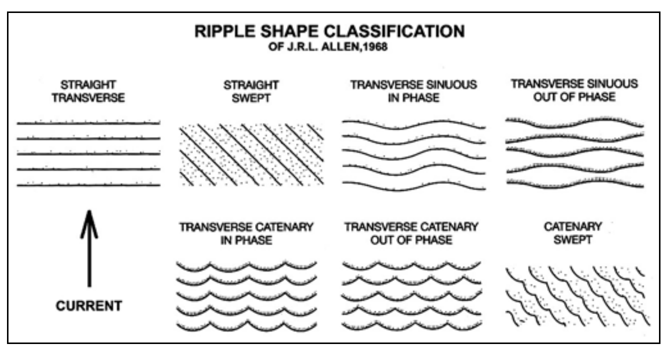

Figure 61—Classification of ripple shapes in map view.

Giant Current Ripple Fields

Camas Prairie has four different giant current ripple fields, one associated with each of the four inflow sublake notches. The three eastern fields merge together farther out in the basin, whereas the Duck Pond Pass system stands alone. In map view the giant current ripples are convex downcurrent, with the central axes of individual ripple fields emanating from the sublake notches [Fig. 9]. Within individual fields, more than one axis can sometimes be recognized, suggesting that more than one flow regime was responsible, although whether these were separate synchronous currents or sequential currents is not apparent. Aerial photographs show individual ripple trains within each of the ripple fields, except for the Big Creek Pass system that has only one clearly recognized ripple train. Table 2 [at end] summarizes the characteristics of the ripple fields and trains.

Wills Creek Ripple Field is the largest and most complex of the four fields, containing five ripple trains that cover more than eight square miles. Ripple train W1 lies on the right [west] side of the field fairly close to the notch and consists of straight swept to straight transverse normal dunes [Fig. 9, Fig. 19]. Estimated wavelengths are about 200 ft [60 m] with heights of 6 to 8 ft [2-3 m]. These GCRs may have extended farther to the east but have been modified or replaced by larger dunes of the W3 ripple train. The GCRs die out to the right [west] into a very narrow north-south strip, largely devoid of GCRs, that separates the Wills Creek field from the Markle Pass field [Fig. 9]. Flood currents from the two notches may have interfered along this strip.

The W2 ripple train, the most extensive in the basin, extends from the Wills Creek notch to the southernmost part of the Camas Prairie Basin, over a distance of six or seven miles, and is more than a mile wide. The GCRs form transverse, sinuous, mostly in-phase, normal dunes with some bifurcations. The dunes are not consistently in phase, and locally they appear out of phase. In general, ripple size decreases downcurrent, but not in a consistent manner. The distal portions of the ripple train probably received contributions from Markle Pass. Two small anomalous pits occur in the distal part of the train [location given in Table 2 (at end)] that are closed depressions with raised rims. These may represent locations of melted icebergs grounded during late flood flow.

Ripple train W3 contains the largest GCRs in the basin. These normal dunes are straight transverse to transverse sinuous in-phase. From a traverse across six of the largest GCRs, their median wavelength is 462 ft [141 m], with a median height of 20 ft [9.1 m]. The largest individual GCR has a wavelength of 951 ft [290 m] and a height of 57 ft [17 m].

Ripple train W4 lies on the expansion bar below the Wills Creek notch. Large GCRs are arcuate transverse to transverse sinuous, more in-phase than out-of-phase.

Ripple train W5 runs below and along the right [west] side of the Wills Creek expansion bar on a steep slope. The train consists of a single series of 13 large, arcuate transverse dunes, convex downcurrent. The dunes are strongly asymmetric with shorter stoss slopes, and when corrected for slope, they have steeper stoss slopes that resemble antidunes [discussed below]. These may represent the very latest flood flow.

Big Creek Pass Ripple Field consists of a single ripple train, less than 0.1 square mile [< 26 hectares] in area, that extends below the lower expansion bar on a steep slope [Fig. 9]. Although somewhat smaller, the six dunes are very similar to the antidunes of Wills Creek Pass, being even more strongly asymmetric.

Markle Pass Ripple Field covers more than one square mile and has three recognizable ripple trains [Figs. 9, 25]. The two distal trains are normal dunes that differ mainly in size, M1 having the smaller dunes. The M1 train is constrained by a steep slope on the right [west] side and by a transverse ridge at the distal end. M2 ripple train is more complex, varying from straight swept dunes in the proximal end to straight transverse and transverse sinuous more-or-less in phase. A narrow strip between this ripple train and the Wills Creek ripple field has only a few very low, south-oriented dunes. As mentioned, the two main currents may have interfered along this strip. Between the proximal end of this ripple train and Markle Pass notch is an anomalous area in which dunes are very short and discontinuous, with no consistent orientation, perhaps a result of interfering flood currents.

The M3 ripple train lies along the left side and below the highest Markle Pass expansion bar, similar to and symmetrical to the W5 train from Wills Creek Pass. It is a series of five large arcuate transverse antidunes on a steep slope.

Duck Pond Pass Ripple Field is a small [less than one square mile] ripple field that changes character downcurrent along a narrow valley [Figs. 9, 35]. GCRs change from antidunes on a very steep slope [11.73%], to reverse dunes in a straight swept to straight transverse train on a steep slope [6.74%], to normal straight transverse dunes along a low-gradient [0.96%] creek bottom, back to reverse straight transverse dunes on a steeper slope [3.54% to 7.09%]. Perhaps slope angle determines whether normal or reverse dunes form, with normal dunes originating on low slopes less than 2% and reverse dunes forming on slopes steeper than about 3% [Fig. 62].

Characteristics of Giant Current Ripples

In V.R. Baker's 1973 study of giant current ripples in the scablands of eastern Washington, he used terms derived from J.R.L. Allen [1968]. Figure 63A illustrates the terminology Baker used to describe giant current ripples, and Figure 63B shows the terms used in this study. Apparently neither Allen nor Baker considered the slope on which these bedforms occur to have been significant, but many of the GCRs at Camas Prairie formed on slopes that are not insignificant, so Figure 63C illustrates the way height was determined at Camas Prairie.

Aside from the small difference in the definition of dune height, terms are similar. This report uses *wavelength* rather than *chord*, but the definition is the same, being the distance from trough to trough. *Ripple index* is defined as wavelength/height and is the same as *vertical form-index* of Allen and Baker. *Asymmetry* of GCRs is defined as the ratio of the length of the stoss side of the dune to the length of the lee side [this is the *ripple symmetry index* of the AGI glossary (Tanner, 1960)]. Apparently all of Baker's [1973] GCRs had longer stoss sides than lee sides, and so he did not report this characteristic, but at Camas Prairie significant differences occur, and the term is useful.

In this study, continuous profiles of GCRs were not surveyed; rather, only three points were measured: the elevations of two troughs and the included crest, and the distances between them. Most traverses used two methods – a pace-and-compass plus handlevel measurement, and waypoints at the same three points recorded by a WAAS-enabled GPS. Where significant relief occurred, the two methods gave similar results [Fig. 64].

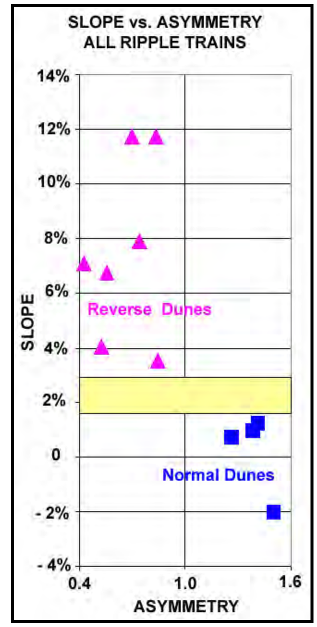

Figure 62—Normal dunes formed on more gentle slopes.

Some traverses were measured by GPS alone, and in a few areas of low relief the elevations were insufficiently accurate to determine heights, although the distances are accurate to within about 10 feet.

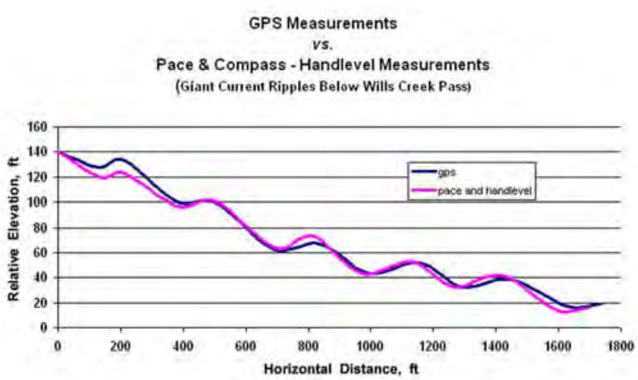

Figure 64—Comparison of data from two methods used to measure giant current ripples.

Pardee [1942] measured some of the giant current ripples and reported a range of wavelengths from a few feet to 500 ft [1-152 m], with a mean of 250 ft [76 m] and heights of less than a foot to 50 ft [<1-15 m], averaging 15-30 ft [4.6-9.1 m]. Pardee did not distinguish different types of giant current ripples, nor did he specify locations where he measured them. From his estimates, however, I believe he measured the most common type of ripple that occurs out in the flats of Camas Prairie, referred to here as normal giant current ripples.

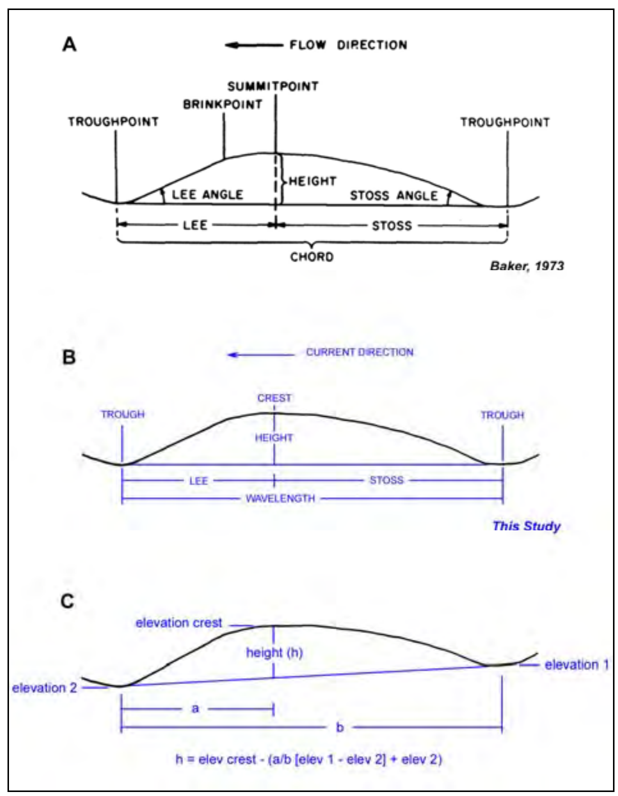

Figure 63—Terminology used to describe giant current ripples.

Normal Giant Current Ripples 92 normal GCRs were measured in seven ripple trains, 29 of which have full measurements from four ripple trains. These four trains are illustrated in Figure 65, where the upper diagram shows relative elevations as a function of distance, and the lower figure shows relative heights as a function of distance, an attempt to correct for the slope on which the GCRs formed.

The mean values of all normal GCRs are: wavelength, 259 ft [79 m]; height, 10.7 ft [3.4 m]; ripple index, 34; and asymmetry, 1.51. The Big GCRs traverse [locations of traverses are shown in Fig. 9] was selected to measure the largest

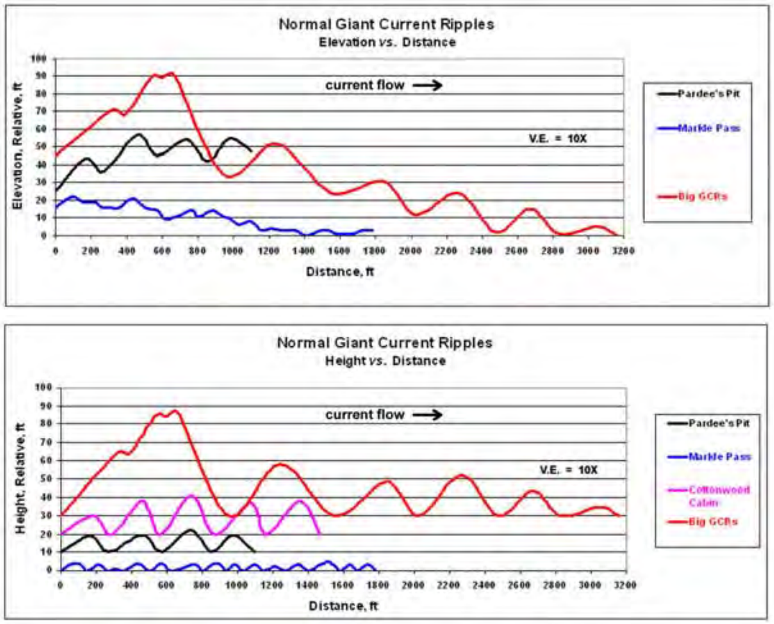

Figure 65—Profiles of normal giant current ripples. Locations of profile traverses shown in Figure 9.

GCRs at Camas Prairie. Six GCRs have a median wavelength of 462 ft [141 m], a median height of 20 ft [6 m], a resulting ripple index of 24, and a median asymmetry of 1.42. The largest dune has a wavelength of 951 ft [290 m] and a height of 57 ft [17 m], with secondary ripples on the stoss side. The Cottonwood Cabin traverse contains the second largest GCRs, with a median wavelength of 291 ft [89 m] and height of 18 ft [5.5 m], and it is actually closer to the sublake notch than the Big GCR traverse. Pardee's Pit traverse is almost half way down the entire ripple field, near the gravel pit described by Pardee [1942], and has smaller GCRs. The smallest normal GCRs measured are in the Markle Pass traverse, where median measurements are: wavelength, 122 ft [37 m]; height, 3 ft [1 m]; ripple index, 38; and asymmetry, 1.27. These normal GCRs are at once the smallest and yet the closest to a sublake notch, illustrating the complexity of the GCR fields. Measurements of GCRs and full traverse data are given in Table 3 [at end].

As the size of giant current ripples generally decreases to the south, so also does the size of the constituent gravels. Toward the north end of the ripple field, coarse gravels are exposed in a gravel pit (visited by the GSA field trip in 2003; Smyers and Breckenridge, 2003), where one can observe poorly sorted open-work boulder-cobble-pebble gravel in foreset beds [Fig. 66]. Most clasts are subangular, but they range from angular to well rounded, and blocks up to five ft diameter [1.5 m] are common.

In a gravel pit in the distal [south] half of the ripple field, Pardee [1942] described *subrounded pebbles [8-20 mm] with scant sandy matrix, loosely compacted, distinctly stratified dipping parallel to the south face*. His sketched cross-section shows foreset beds dipping 23°. In a nearby gravel pit, foresets of open-work discoidal pebble gravel dip about 14° to the south [Fig. 67].

Figure 66—Coase gravel in a giant current ripple in north part of Camas Prairie ripple field. Crude foreset beds dip about 20° toward observer.

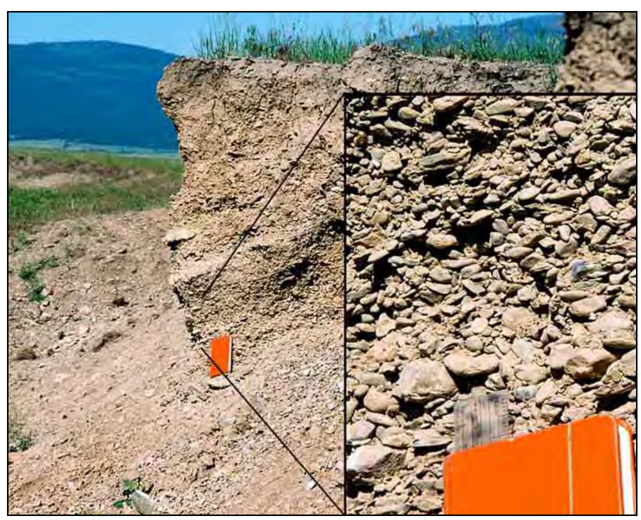

Figure 67—Pebble gravel in a giant current ripple in south part of Camas Prairie ripple field, view to west.

Reverse Giant Current Ripples Twelve reverse GCRs were observed in two ripple trains below Duck Pond Pass, eight of which have full measurements. These two trains are illustrated in Figure 68, which shows relative elevations and relative heights as a function of distance. Note the relatively steep slopes on which the reverse GCRs formed.

The mean values of all reverse GCRs are: wavelength, 278 ft [85 m]; height, 12 ft [3.7 m]; ripple index, 31; and asymmetry, 0.61. The maximum wavelength is 591 ft [180 m] and the maximum height is 37 ft [11 m].

Curiously, the two reverse GCR ripple trains are separated by a ripple train of normal GCRs along Cottonwood Creek, where the gradient is significantly lower. The slope of the upper reverse GCRs is 6.74%, the intermediate normal GCRs are on a slope of 0.96%, and the slope of the lower train of reverse GCRs is 3.54%. It is this sequence of GCRs that leads to the suggestion that reverse GCRs may have formed because of the steeper slopes [refer back to Fig. 62].

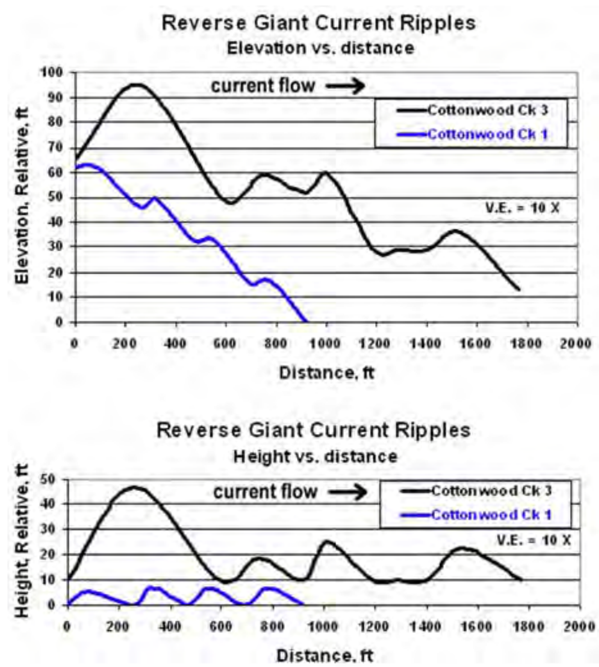

Figure 68—Profiles of reverse dunes. Locations of profile traverses shown in Figure 9.

Antidunes 29 antidunes were measured in four ripple trains, all of which have full measurements. These four trains are illustrated in Figure 69. Note the very steep slopes on which the antidunes formed.

The mean values of all antidunes are: wavelength, 269 ft [82 m]; height, 12 ft [3.7 m]; ripple index, 27; and asymmetry, 0.70.

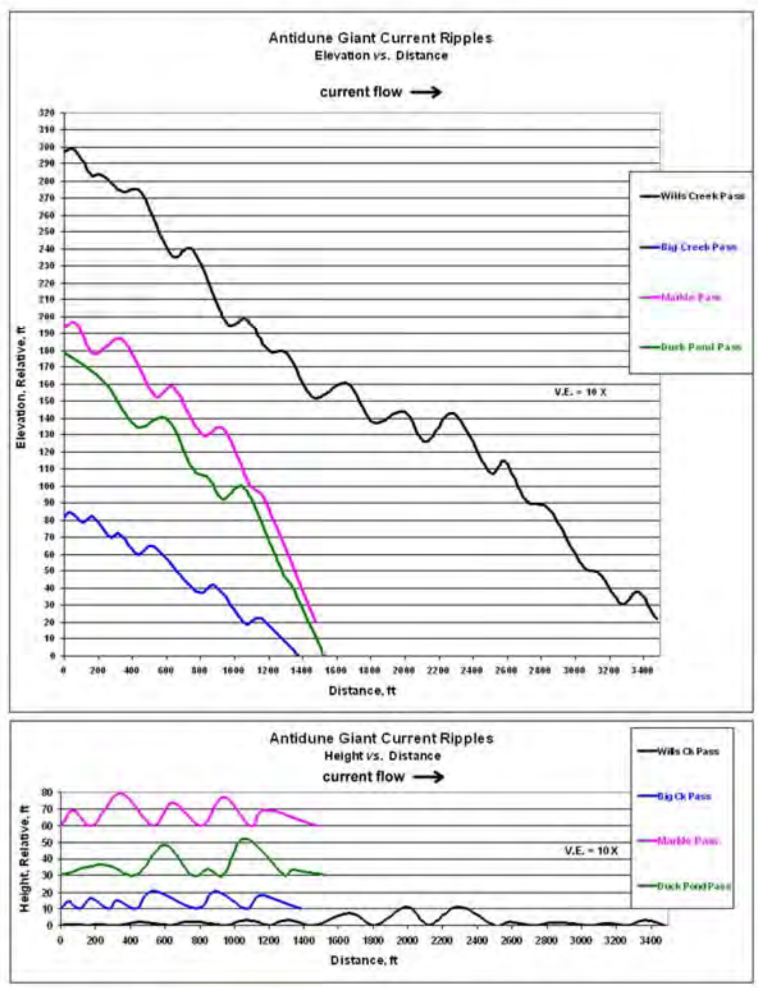

Figure 69—Profiles of antidunes. Locations of profile traverses shown in Figure 9.

As noted, one train of antidunes formed below each of the notches, either alongside an expansion bar [Wills Creek Pass, Markle Pass] or at the distal end of the expansion bar [Big Creek Pass, Duck Pond Pass]. The common characteristics of the antidunes include position, steepness of slope, stoss slopes shorter than lee slopes, and, distinct from all other GCRs, the simple arcuate shape of the dunes [Fig. 70].

It is suggested that these are antidunes, but, unfortunately, no exposures are available to support this with observations of shallow backset beds. Because of the very large clast size and poor sorting, proper excavations are difficult. In several shallow pits, cobbles dip $5^{o} – 20^{o}$ in the upcurrent direction, but it is not possible to attribute these to backset bedding rather than imbrication. Lister [1981] described shallow backset gravels that he

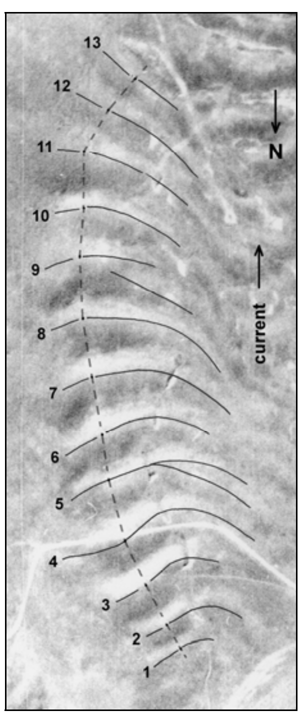

Figure 70—Air photo of antidunes at Wills Creek Pass. Lines show crests; dashed line is measurement traverse.

attributed to antidune bedforms in a gravel pit north of Markle Pass, but I was unable to find any in the currently open gravel pits.

Camas Prairie might provide an interesting field lab for studying antidunes, because they are rarely preserved. Leeder [1982, p.92], discussing antidunes, said *These sets have a low preservation potential…since any deceleration of the flow will cause a plane bed to develop, causing destruction of the antidune.* Antidunes at Camas Prairie may have been preserved because of the unique hydraulic regime; flow did not decelerate, rather, it ended abruptly when lake level dropped to the notch floor. From Leeder's Eq. 8.3, the velocity of the supercritical flow forming these antidunes would have been about 120 ft/s [37 m/s], but it is unclear whether these equations, based on observational data limited entirely to sand-size particles, would scale up to be valid for similar bedforms in gravel.

All Giant Current Ripples. Combining all GCR data for Camas Prairie, 133 GCRs were measured, 66 of which have full data. From the set of 66 GCRs:

Wavelength	ranges from 90 to 951 ft	with a mean of 270 ft;	[27-290 m, 82 m]
Height	ranges from 1 to 57 ft	with a mean of 12 ft;	[0.3-17 m, 3.7 m]
Ripple Index	ranges from 14 to 90	with a mean of 31;	
Asymmetry	ranges from 0.24 to 2.80	but a mean is not informative, because normal GCRs are underweighted in the sample	

Analysis of Giant Current Ripple Data

Height vs. Wavelength Heights of individual GCRs correlate with wavelength; high dunes are more widely spaced. Figure 71 shows this relationship for all GCRs combined. Normal GCRs have a higher correlation coefficient than reverse GCRs, and antidunes as a group correlate the most poorly [Fig. 72], although within some individual antidune ripple trains the correlation is good [Wills Creek Pass, 0.84, Big Creek Pass, 0.88].

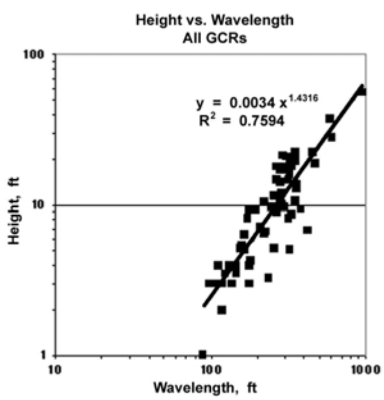

Figure 71—Relationship of height to wavelength for all giant current ripples.

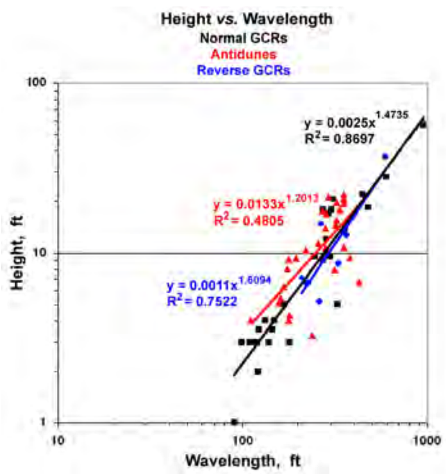

Figure 72—Relationship of height to wavelength for GCRs separated by type.

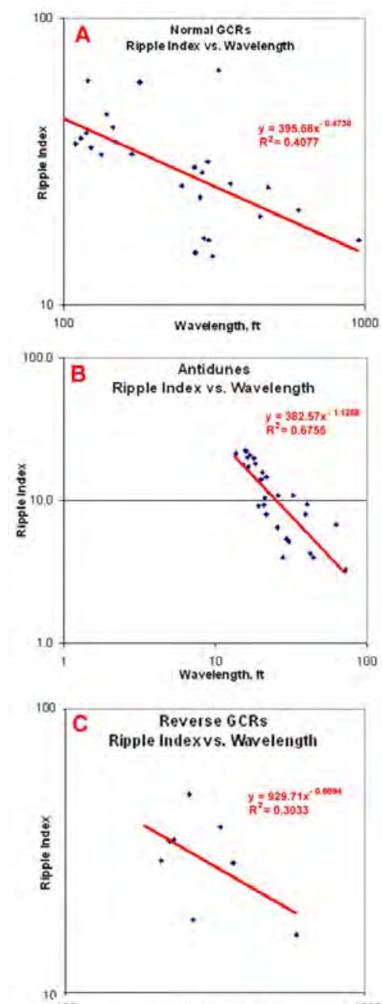

Figure 73—Relationship of ripple index to wavelength.

Ripple Index vs. Wavelength
Ripple index has an inverse relation with wavelength, although the correlation is weak. Figure 73A shows ripple index vs. wavelength for normal GCRs, along with their derived regression equation. Figures 73B and 73C show relationships for antidune GCRs and reverse GCRs; R^2 values are higher for antidunes and lower for reverse dunes.

Asymmetry vs. Wavelength Asymmetry is not related to wavelength. Correlation coefficients for all three types of GCRs range from 0.10 to 0.13.

Height vs. Steepness of Dune Slopes Higher GCRs have steeper slopes, both stoss slopes and lee slopes. Figure 74 shows height vs. slope angle for normal GCRs and their derived regression equations.

Comparison of Giant Current Ripples at Camas Prairie with Other Ripple Studies

GCRs at Camas Prairie are significantly different from normal sand ripples in more than just size. They show close correspondence to GCRs created by the Missoula flood below the ice dam in the scablands of eastern Washington and, perhaps more closely analogous, to sublake GCRs formed in the Altai flood of Siberia.

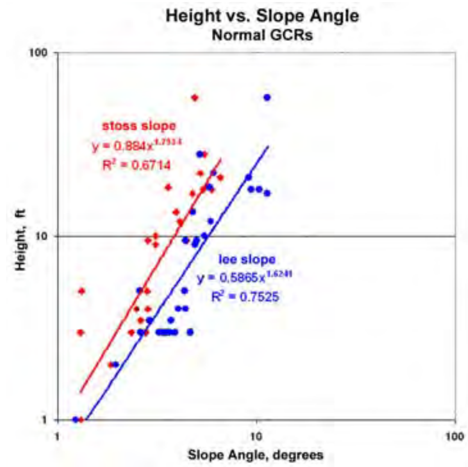

Figure 74—Relationship of height to slope angle for normal GCRs.

Normal GCRs at Camas Prairie can be compared with the characteristics of both sand ripples and other giant current ripples. Figure 75 shows a plot of height vs. wavelength for normal dunes at Camas Prairie, along with a regression equation. Also plotted on the diagram are the regression equations derived from classic studies of sand ripples [Allen, 1968; Flemming, 1988] and from giant current ripples in the scablands of eastern Washington [Baker, 1973]. Clearly, the giant current ripples from both eastern Washington and Camas Prairie have similar characteristics, and both are distinct from sand ripples.

Figure 75 also allows a comparison with similar giant current ripples created by the Pleistocene Altai flood at the head of the Ob River drainage of Siberia [Rudoy and Baker, 1993]. Giant current ripples formed at several places on the floor of Lake Kuray-Chuya, an ice-dammed lake system that covered two contiguous basins. From pace and hand-level measurements of five of the largest GCRs in the largest ripple field, just east of the Tyetyo River in the Kuray Basin, the mean wavelength is 462 ft [141 m], mean height is 26 ft [7.9 m], and the mean ripple index is 18 [http://www.mines.edu/academic/geology/faculty/klee/AltaiFlood.pdf].

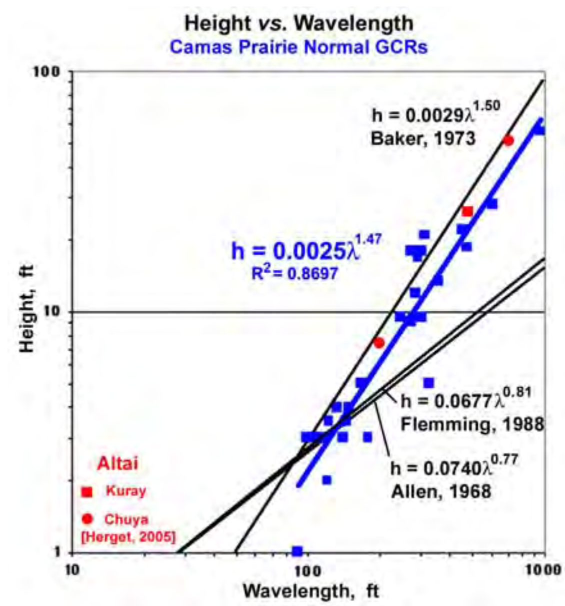

Figure 75—Height-wavelength relationship for normal GCRs at Camas Prairie compared with data from scablands of Eastern Washington [Baker, 1973], sand ripples [Allen, 1968; Flemming, 1988], and GCRs from the Altai flood of Siberia.

Mean asymmetry is either 1.8 or 0.56, depending on whether these are normal or reverse dunes, respectively. The shorter dune sides face east, which is *up* the main drainage. Rudoy interpreted these as normal GCRs [pers. comm., 2003], and his interpretation thus invoked giant eddy currents that flowed up the drainage, the currents presumably created by the lower ice dam or hydraulic dam [Rudoy, 1998, Figure 16.2; reproduced in above internet citation]. Carling [1996] also interpreted these as normal dunes, but suggested they formed during the final stages of the drainage of the lake, when local topography directed drainage currents to the east, an interpretation later supported by Herget [2005]. The three Altai data points in Figure 75, representing the means of the Altai GCRs from three different ripple trains, show, albeit for a limited sample, that these sublake GCRs are clearly related to those at Camas Prairie.

As shown previously, ripple index correlates inversely with wavelength. Figure 76 shows this relation for normal GCRs at Camas Prairie, along with regression lines and equations for sand ripples and scabland GCRs. As with height vs. wavelength, the relationship between ripple index and wavelength is similar for GCRs from both eastern Washington and Camas Prairie, and both are opposite to the relationship for sand ripples.

The positive relationship between height and steepness of dune slopes shown above for Camas Prairie is opposite to that shown by sand ripples, as illustrated in Figure 77. Once again, a similar relationship exists between Camas Prairie and eastern Washington GCRs, although Baker's slope angles are steeper than those at Camas Prairie. This can be explained, at least in part, by the measurement methods used to obtain the data; Figure 78 shows how lower slope angles would result from using three point data.

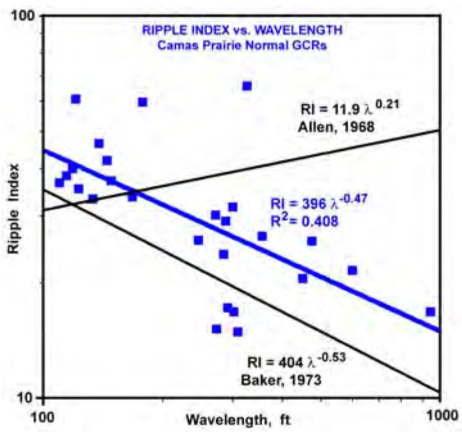

Figure 76—Ripple index-wavelength relationship for normal GCRs at Camas Prairie compared with data from scablands of Eastern Washington [Baker] and sand ripples [Allen]. Regression equations for Allen and Baker derived from Baker's Figure 40 [1973, p.53].

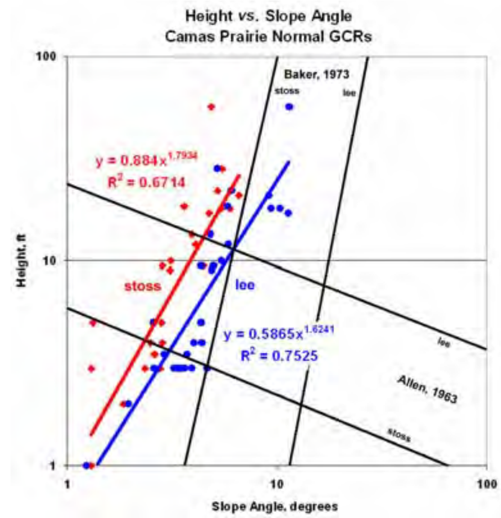

Figure 77—Height-slope angle relationship for normal GCRs at Camas Prairie compared with data from scablands of Eastern Washington [Baker] and sand ripples [Allen].

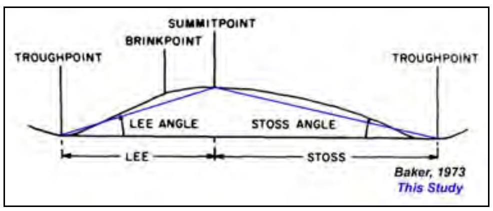

Figure 78—Slope-angle calculations. Method of this study yields lower angles.

Analysis of Giant Current Ripple Data to Estimate Paleohydraulic Parameters

In Victor Baker's [1973] classic study of GCRs in the scablands of eastern Washington, he estimated paleohydraulic parameters from analysis of channel geometry and related them to GCR characteristics. The size of GCRs can be related to the intensity of flood discharge. Using the relationships Baker derived from this study, one can attempt to estimate similar paleohydraulic parameters at Camas Prairie using the GCR data.

Baker [1973] derived equations relating both height and wavelength of GCRs to depth of water. In his analysis, he found much more consistent relationships to the depth-slope product than to depth, so one can look at this relationship at Camas Prairie. Given the choice of wavelength or height [both have correlation coefficients greater than 0.90], one might choose to use wavelength, not only because wavelength shows a slightly better correlation than height, but mainly because wavelength is less susceptible to post-deposition modification by erosion. Use of Baker's Equation 16 [Baker, 1973, p. 59]:

$$\lambda_\mu = 393.5\,(DS)^{0.66},$$

where λ_μ is mean wavelength, D is depth, and S is energy slope [the slope of the line joining the elevations of the energy heads of a stream],

yields the data in Table 4 [at end]. From the depth-slope product, one can derive an estimate of depth from an assumption of energy slope. As a first approximation, the topographic slope can be used, which yields depths ranging from 9 to 144 ft [Tbl. 4]. These depths are shallower than anticipated, and several interpretations could be offered:

[1] all of the GCRs were formed during waning stages of flood flow, when depths were shallow;
[2] the empirical equation derived for flood flows in the scablands of eastern Washington is not valid here; or
[3] the assumption that energy slope was equal to the surface slope is not valid.

Addressing the third possibility, almost all of the topographic slopes at Camas Prairie are greater than those in eastern Washington, by as much as an order of magnitude. If one assumes an average energy slope of 0.003, calculated depths then range from 157 to 593 ft [Tbl. 4]. If the calculated depth is compared with the maximum depth at the end of flood flow [that is, when Wills Creek Pass was abandoned], a positive correlation is obtained [Fig. 79].

Baker [1973] also derived the relationship between mean flow velocity [discharge velocity] and wavelength of GCRs. From his Figure 53 [Baker, 1973, p.62]:

$$\lambda_{\mu} = 8.24\ V^{0.870}$$

where λ_{μ} is mean wavelength and V is velocity,

which can be applied to the Camas Prairie GCRs to calculate velocity, as shown in Table 5 [at end]. Calculated velocities range from 17 to 64 ft/sec [5.2-19 m/s] and are very similar to those calculated by Baker [this is a one-variable relationship, and the wavelengths of GCRs in both areas are similar, so velocities would be similar].

Without reliable values for depth-slope and velocities, one cannot calculate Froude numbers or stream power. For the same reason, critical tractive forces cannot be estimated usefully.

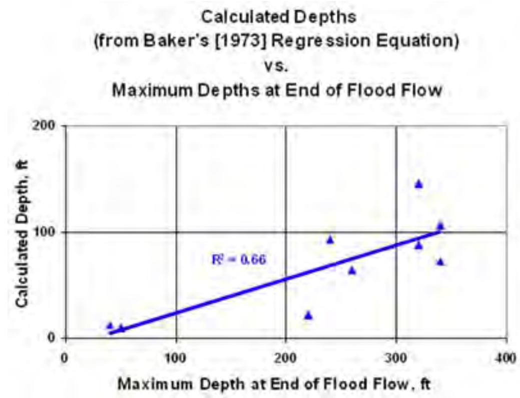

Figure 79—Correlation of depths calculated from Baker's equation to maximum depths at the time that flood flow ceased.

SUMMARY

In the late 1930's, some twenty years after he described the evidence for a glacial lake at Missoula, Joseph T. Pardee had the insight to recognize that catastrophic lake-bottom currents had torn through the Camas Prairie. Despite his immensely understated title of "*Unusual* Currents in Glacial Lake Missoula", Pardee was fully aware that no such catastrophic currents had ever been described in the professional literature, except for the arguments for a catastrophic flood in eastern Washington being made at the time by the controversial J Harlan Bretz.

In the seventy years since, little attention has been given to such lake-bottom currents, although considerable work has been published to document the catastrophic channel flood flows of the Missoula Flood below the failed ice dam. It is important to recognize the difference: conventional channel flood flows, catastrophic or not, are driven by events upstream that force the flood downstream; lake-bottom currents, of the kind described here, are driven by an event downstream -- the failure of a glacial dam that basically pulls the plug on the glacial lake -- that forces the flood to proceed upstream.

Camas Prairie is in a simple drainage basin about in the middle of glacial Lake Missoula, but situated such that complex currents developed in the basin when the falling lake level worked its way up from the failed damsite. Water in Camas Prairie Basin, initially about a thousand feet deep, first flowed west through Rainbow Lake Pass, and as lake level dropped in the basin, water flowed in from Little Bitterroot Valley and Mission Valley. At this time, all of the lake-bottom currents were flowing uphill to enter the basin, transporting bedload gravels upslope and over the divide. This inflow was progressively more restricted as lake level fell, with lake-bottom topography forcing flow to concentrate in the sublake notches.

Lake-bottom currents approaching the Camas Prairie Basin transported bedload gravels up the slope and deposited them behind local obstructions to form unusual lee gravels. In likewise fashion, washover bars formed just inside the basin rim where bedload gravels were transported up the slopes and dumped just over the top.

Each sublake notch experienced erosion of an unusual nature – blocks of bedrock were torn out by vertical vortices called kolks, which produced jagged bedrock floors in rip channels bounded by steep walls. This was truly catastrophic erosion, with billions of cubic feet of rock ripped out in a matter of hours or days. The scablands created were not in fluvial channels; rather, they are perched high on the basin rim.

Expansion bars formed below each of the sublake notches where foreset beds of open-work boulder-cobble-pebble gravel were deposited. Within the gravels are blocks of bedrock that probably represent fallout from suspension in dissipating kolk vortices. Most of the material in the expansion bars probably came from the notches themselves. Aqueous deposition rates were probably hundreds of millions of cubic feet of gravel per day. Closed depressions, or pools, on the surfaces of the expansion bars suggest chute and pool structures, but lack of exposures precludes verification.

When Lake Missoula's ice dam failed, most water from Camas Prairie, as well as from Little Bitterroot Valley and Mission Valley, poured directly west toward Eddy Narrows through Rainbow Lake Pass. The pass was under about 300 ft of water initially, and flood waters tore out about 360 ft more of very competent bedrock, primarily by kolk action. Flood currents carved a long, straight, remarkably flat rip channel pocked by kolk pits. Flood discharge at the end of the rip channel crashed into Locust Hill, a wedge-shaped bedrock hill that split the flood currents into northwest and southwest components that deposited flood gravels in several large expansion bars. When local lake level dropped about 500 ft [150 m], the Rainbow Lake outlet was abandoned, and all flow through Camas Prairie turned south to the Perma outlet.

The outlet at Perma shows similar severe erosion. Perma Ridge was cut by five stepped rip channels with kolk pits that indicate the flood currents were most effective against the west abutment of the basin as they took the most direct route to the failed damsite. Discharge from Camas Prairie, probably in conjunction with flood flow down the Flathead Valley, severely impacted the far wall of the Flathead Valley, tearing out large kolk pits and cutting semicircular rip walls.

Camas Prairie is notable for its giant current ripples, or large-to-very-large, two-dimensional, flow transverse, sinuous, in-phase, subaqueous gravel dunes, which formed below each of the four inlet sublake notches and merged farther out on the basin floor. Giant current ripples cover approximately 10 square miles [26 km^2], but they once covered a considerably larger area.

Giant current ripple wavelengths range from 90 to 951 ft [27-290 m] with a mean of 270 ft [82 m], height ranges from 1 to 57 ft [0.3-17 m] with a mean of 12 ft[3.7 m], ripple index ranges from 14 to 90 with a mean of 31, and asymmetry ranges from 0.2 to 2.8. Giant current ripples are subdivided into normal, reverse, or antidunes. Normal dunes, the most common type, have shorter, steeper lee slopes, and their shape is generally transverse sinuous in-phase, with bifurcations common. Reverse dunes have shorter, steeper stoss sides, but their shape is similar to normal dunes. Antidunes are notably asymmetric, with shorter stoss sides, but they have short, arcuate transverse, convex-downcurrent shapes.

Normal giant current ripples account for more than 90% of the ripple fields. They have a mean wavelength of 259 ft [79 m], height of 11 ft [3.4 m], ripple index of 34, and asymmetry, 1.5; the largest has a wavelength of 951 ft [290 m] and a height of 57 ft [17 m]. Size of GCRs in general decreases away from the notches, but not in a consistent manner. Constituent gravels similarly decrease in size to the south, from boulder-cobble gravels to pebble gravels, all of which have open-work texture. Foreset bedding is crude, and dips vary from 14 degrees to 23 degrees.

Reverse dunes have been recognized only in the Duck Pond Pass system, although they may well occur in the other systems but have not been recognized because their shape is similar to normal dunes. Two trains of reverse dunes, on fairly steep slopes, are separated by a train of normal dunes on a gentle slope, suggesting that slope may be a causative factor.

One train of antidunes formed on a steep slope along, or at the end of, each of the expansion bars. Along with their position, their shape is different from all other GCRs in the basin: they are simple, short, arcuate dunes. Unfortunately, no exposures are available to document backset bedding.

The characteristic of GCRs most resistant to post-depositional change is wavelength. Both height and ripple index correlate with wavelength: higher dunes are more widely spaced, and ripple index varies inversely with wavelength. Asymmetry shows no correlation.

Giant current ripples at Camas Prairie are significantly different from normal sand ripples in more than just scale. They show close correspondence to GCRs created by the Missoula flood in the scablands of eastern Washington and, more closely analogous, to GCRs formed on the floor of Lake Kuray-Chuya by the Altai flood in Siberia.

Antidunes and chute-and-pool structures normally are not preserved because waning fluvial flows transition into lower flow regimes that modify the bedforms. What was unique at Camas Prairie was the paleohydraulic regime: current velocities did not decrease in a gradual manner; rather, they dropped abruptly when lake level fell below the sublake notches.

The flood features at Camas Prairie document catastrophic sublake currents that have been described only here and in Siberia. The unique paleohydraulic regime at Camas Prairie that resulted from a catastrophic failure of the ice dam may have preserved aqueous depositional bedforms that are rare [antidunes] or unknown [chute and pool structures] outside of theoretical or experimental studies. Camas Prairie preserves a natural laboratory for their investigation.

ACKNOWLEDGEMENTS

I thank John E. Warme, Colorado School of Mines, for his critical review of an earlier version of this paper and his numerous suggestions for clarification. Norman B. Smyers, US Forest Service, also reviewed an earlier version. Seth Makepeace, Confederated Salish and Kootenai Tribes of the Flathead Nation, assisted my work on the Flathead Indian Reservation and provided modern aerial photography. Judy Reese, US Forest Service, made available aerial photography in the Lolo National Forest. Numerous ranchers in and around Camas Prairie graciously allowed me to tromp about on their land; I thank them for their Montana hospitality.

REFERENCES

Allen, J.R.L., 1968, Current ripples, their relation to patterns of water and sediment motion: Amsterdam, North-Holland Publishing, 433 p.

Allen, J.R.L., 1982, Sedimentary structures, their character and physical basis, volume II: Amsterdam, Elsevier Scientific Publishing, 663 p.

Alt, David, 2001, Glacial Lake Missoula and its humongous floods: Missoula, MT, Mountain Press, 199 p.

Ashley, G.M., 1990, Classification of large-scale subaqueous bedforms: A new look at an old problem: Journal Sedimentary Petrology, v. 60, no. 1, p. 160-172.

Baker, V. R., 1973, Paleohydrology and sedimentology of Lake Missoula flooding in Eastern Washington: Geological Society of America Special Paper 144, 79 p.

Baker, V.R., editor, 1981, Catastrophic flooding, the origin of the channeled scabland: Benchmark Papers in Geology, v. 55, Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross, 360 p.

Bretz, J H., 1923, The Channeled Scablands of the Columbia Plateau: Journal of Geology, v.31, p.617-649.

Bretz, J H., 1969, The Lake Missoula floods and the Channeled Scabland: Journal of Geology, v. 77, p. 505-543.

Carling, P.A., 1996, Morphology, sedimentology and palaeohydraulic interpretation of large gravel dunes: Altai Mountains, Siberia: Sedimentology, v. 43, p. 647-664.

Flemming, B.W., 1988, Zur Klassifikation subaquatischer, stromungstrans versaler Transportkorper: Boch. geol. u. geotechn. Arb., v. 29, p. 44-77.

Herget, Jürgen, 2005, Reconstruction of Pleistocene ice-dammed lake outburst floods in the Altai Mountains, Siberia: Geological Society of America Special Paper 386, 118 p.

Leeder, M.R., 1982, Sedimentology, process and product: London, Allen & Unwin, 344 p.

Lister, J.C., 1981, The sedimentology of Camas Prairie Basin and its significance to the Lake Missoula floods, unpublished thesis, University of Montana, Missoula, 66 p.

Matthes, G.R., 1947, Macroturbulance in natural stream flow: Transactions American Geophysical Union, v. 28, no. 2, p. 255-265.

Pardee, J.T., 1910, The glacial Lake Missoula: Journal of Geology, v. 18, p.376-386.

Pardee, J.T., 1942. Unusual currents in Glacial Lake Missoula, Montana: Geological Society of America Bulletin, v. 53, p. 1569-1600.

Rudoy, A. N., 1998, Mountain ice-dammed lakes of southern Siberia and their influence on the development and regime of the intracontinental runoff systems of north Asia in the Late Pleistocene, *in* Benito, G., Baker, V.R., and Gregory, K.J., eds., Palaeohydrology and environmental change: Wiley, p. 215-234.

Rudoy, A.N., and Baker, V.R., 1993, Sedimentary effects of cataclysmic late Pleistocene glacial outburst flooding, Altay Mountains, Siberia: Sedimentary Geology, v. 85, p. 53-62.

Smyers, N.B., and Breckenridge, R.M., 2003, Glacial Lake Missoula, Clark Fork ice dam, and the floods outburst area: northern Idaho and western Montana: Geological Society of America *[Annual Meeting]* Field Guide 4, 15p.

Tanner, W.F., 1960, Shallow water ripple mark varieties: Journal Sedimentary Petrology, v.80, p.481-485.

TABLES
2 - 5

Table 2--Giant Current Ripples in Camas Prairie Basin
Ripple Fields and Ripple Trains

Ripple Train Characteristics					Giant Current Ripple Characteristics									
Ripple Train *	Position in Field	Current Direction	Length, typical ft	Width, typical ft	Ripple Type *	Shape*	Number measured	Wavelength*, ft	Height*, ft	Asymmetry*	Ripple Index*	Slope %	Length, typical, ft	Notes
* ripple trains are shown in Figure 9					* *Italic = estimated*	* see Figure 61		* median given where available, otherwise mean [μ] or *estimated*						
				Big Creek Pass Ripple Field										
B1	proximal	N 60 W	900	1000	antidunes	3-D arcuate transverse	6	224	7.2	0.53	29	4.02	1000	Only ripples that clearly emanate from
		[N70-60W]				convex downcurrent								Big Creek Pass.
														Below largest expansion bar.
				Wills Creek Pass Ripple Field										
W1	intermediate	S 20 W	5000	1000	*normal*	straight swept to		*200*	*6-8*		*30*		800	May be earliest of ripple trains; may have
	right [W]	[S 20-40 W]				straight transverse								been wider originally.
														West side probably constrained by interfer-
														ence with current from Markle Pass.
W2	intermediate	South		6000	normal	transverse sinuous in-phase	4	278	10	1.51	28	-2.13	800	Slope to the north [upcurrent].
	to distal	[S10E to S20W]	31,000			with some bifurcations	23	230 [μ]	5.6 [μ]		41 [μ]		3000	λ from air photos; h est.for 5 GCRs in field.
	axial to		[5.9 miles]				28	189 [μ]	5.1 [μ]		37 [μ]		3000	λ from air photos; h est.for 5 GCRs in field.
	left [E]		[9.5 km]											Distal area with contribution from Markle Pass.
			originally											No GCRs in 2 depressions with raised rims in
			6.6 mi											NW1/4 Sec24 T20N R24W; from grounded ice?
			[10.6 km]											
W3	proximal	S 30 W	6000	4000	normal	straight transverse to	6	462	20	1.42	24	1.23	3500	Largest GCRs in Camas Prairie. Maximum
	axial to right	[S 10-50 W]				transverse sinuous in-phase	5	291	18	1.75	17		2500	wavelength 951 ft; max height 57 ft.
W4	proximal, on	South												
	expansion bar	[S20E to S10W]	2000	2500	*normal*	3-D arcuate transverse to		*300*	*10-12*		*27*		1400	On top of expansion bar.
						transverse sinuous in-phase								
W5	proximal	South	3000	1000	antidunes	3-D arcuate transverse	13	270	15	0.74	21	7.91	1000	On right [W] side of expansion bar;
	right [W]	[S15E to S20W]												may be late stage flood flow

Table 2--Ripple Fields and Ripple Trains [cont'd]

Ripple Train	Position in Field	Current Direction	Length, typical ft	Width, typical ft	Ripple Type *	Shape*	Number measured	Wavelength*, ft	Height*, ft	Asymmetry*	Ripple Index*	Slope %	Length, typical, ft	Notes
Ripple Train Characteristics					**Giant Current Ripple Characteristics**									
					***italic** = estimated*	* see Figure 61		* median given where available, otherwise mean [µ] or *estimated*						
			MARKLE PASS RIPPLE FIELD											
M1	intermediate; [proximal (?) when formed]	South [S20W to S10E]	4000	3000	normal	straight transverse to transverse sinuous in-phase	14	122	3.0	1.27	38	0.73	1600	Constrained by valley slope on right [W]. Below older expansion bars.
M2	intermediate - distal; medial to left [E]	S 10 E [S20E to S20W]	10000 probably ex-tended to 15,000	2000	*normal*	straight swept [N end] to straight transverse and transverse sinuous in-phase with bifurcations		*300* variable	*8-12*		*30*		2000	North end probably had interference from Wills Creek current. Distal GCRs may have merged with those from the Wills Creek Field.
M3	proximal left [E] lateral	South	1500	800	antidunes	3-D arcuate transverse	5	283	14	0.70	19	11.72	700	On left [E] side of latest expansion bar.
			DUCK POND PASS RIPPLE FIELD											
D1	proximal axial	S 30 W	1400	1000	antidunes	3-D arcuate transverse	5	333	7	1.00 0.83 [µ]	45	11.73	1000	On distal end of expansion bar.
D2	proximal to intermediate; in part impacts a transverse ridge	S 40 W chang-ing to S 20 E	5000	1400	reverse	variable; changes from straight transverse to straight swept back to straight transverse	4	226	6.6	0.55	34	6.74	1300	Some GCRs convex upcurrent; these may represent current reflected back from a transverse ridge [see Fig. 6].
D3	intermediate to distal	S 20 E	2500	800	normal	stright transverse	12	205	*4-6*	1.39	*40*	0.96	600	Flood flows were constrained by narrow valley slopes on both sides.
D4	distal	S 25 E [S 10-50 E]	5000	2500	reverse	straight transverse to	5	299	14	0.69	23	3.54	2300	
						transverse sinuous in-phase	3	213	*2-8*	0.42	*43*	7.09	2600	

Table 3--Measurements of Giant Current Ripples
Camas Prairie Basin

Traverse Name[a] / Dune Type / Azimuth / Date / Method	Ripples	Wavelength [ft]	Height [ft]	Asymmetry[b]	Ripple Index[c]	Slope
Big GCRs	c1	951	57	2.33	17	
normal	c2	601	28	0.95	21	
S 53 W	c3	475	19	1.61	26	
29-Jun-04	c4	449	22	1.17	20	
pace and handlevel + GPS[d]	c5	357	14	1.22	26	
[largest GCRs in the basin]	c6	328	5	1.96	66	
	mean	**527**	**24**	**1.54**	**29**	**1.23%**
	median	**462**	**20**	**1.42**	**24**	
Cottonwood Cabin	c1	289	10	1.75	29	
normal	c2	273	18	1.73	15	
S 35 W	c3	311	21	1.39	15	
11-Jul-02	c4	291	17	2.38	17	
pace and handlevel	c5	302	18	1.75	17	
	mean	**293**	**16.8**	**1.80**	**19**	**n/a**
	median	**291**	**18**	**1.75**	**17**	
Pardee's Pit	c1	272	9	1.58	30	
normal	c2	300	10	1.76	32	
S 15 E	c3	284	12	1.43	24	
28-Jun-04	c4	246	10	0.98	26	
pace and handlevel + GPS	**mean**	**275**	**10**	**1.44**	**28**	**-2.04%**
[note uphill gradient]	**median**	**278**	**10**	**1.51**	**28**	
Section 13 normal	23					
S, 30-Jun-04	**mean**	**230**	**5.6**	**--**	**41**	
wavelengths from air photo, 5 heights measured in field						
Section 24 normal	28					
S, 30-Jun-04	**mean**	**189**	**5.1**	**--**	**37**	
wavelengths from air photo, 5 heights measured in field						
Markle Pass	c1	148	4.0	1.62	37	
normal	c2	119	3.0	1.24	40	
S 17-2 W	c3	90	1.0	0.95	90	
29-Jun-04	c4	146	3.5	1.12	42	
pace and handlevel + GPS	c5	123	3.5	1.29	35	
	c6	179	3.0	2.80	60	
	c7	133	4.0	1.54	33	
	c8	99	3.0	1.03	33	
	c9	114	3.0	1.22	38	
	c10	121	2.0	1.06	60	
	c11	139	3.0	1.11	46	
	c12	168	5.0	1.55	34	
	c13	99	3.0	1.68	33	
	c14	109	3.0	1.50	36	
	mean	**128**	**3.1**	**1.41**	**44**	**0.73%**
	median	**122**	**3.0**	**1.27**	**38**	
Wills Ck Pass AD	C1	160	5.4	0.74	30	
antidunes	C2	180	4.3	0.49	42	
S25E-S23W	C3	292	21.3	0.52	14	
13-Sep-05	C4	324	15.7	0.56	21	
pace and handlevel + GPS	C5	256	11.3	0.83	23	
	C6	270	17.8	0.67	15	
	C7	351	20.7	1.06	17	
	C8	319	14.7	1.31	22	
	C9	354	22.2	0.84	16	
	C10	175	8.0	0.55	22	
	C11	324	19.9	0.62	16	
	C12	221	10.3	0.78	21	
	C13	195	9.2	0.89	21	
	mean	**263**	**13.9**	**0.76**	**21**	**7.91%**
	median	**270**	**14.7**	**0.74**	**21**	

[a] traverse locations shown on map [Fig. 9]
[b] asymmetry = (length stoss side) / (length lee side)
[c] ripple index = wavelength / height
[d] GPS is WAAS-enabled

Table 3--Measurements of Giant Current Ripples [cont'd]

Traverse Name[a] Dune Type Azimuth Date Method	**Ripples**	**Wavelength [ft]**	**Height [ft]**	**Asymmetry**[b]	**Ripple Index**[c]	**Slope**
Big Ck Pass AD	c1	111	4.0	0.63	28	
antidunes	c2	166	6.4	0.61	26	
N 69-58 W	c3	157	5.1	0.45	31	
14-Sep-05	c4	351	10.7	0.38	33	
pace and handlevel + GPS	c5	281	10.7	0.60	26	
	c6	316	8.0	0.39	40	
	mean	**230**	**7.5**	**0.51**	**30**	**4.02%**
	median	**224**	**7.2**	**0.53**	**29**	
Markle Pass AD	c1	178	9.2	0.70	19	
antidunes	c2	354	19.7	0.87	18	
S 0-19 E	c3	281	14.1	0.65	20	
17-Sep-06	c4	283	17.1	0.78	17	
pace and handlevel + GPS	c5	380	9.4	0.26	40	
	mean	**295**	**13.9**	**0.65**	**23**	**11.72%**
	median	**283**	**14.1**	**0.70**	**19**	
Duck Pond Pass AD	c1	426	7	1.29	63	
antidunes	c2	333	18	1.09	18	
S 27-44 W	c3	178	4	1.00	45	
18-Sep-06	c4	352	22	0.53	16	
pace and handlevel + GPS	c5	238	3	0.24	73	
	mean	**305**	**10.9**	**0.83**	**43**	**11.73%**
	median	**333**	**6.8**	**1.00**	**45**	
Cottonwood Creek - Traverse 1	c1	259	5.2	0.48	50	
reverse	c2	208	7.1	0.47	29	
S 39 W	c3	223	6.5	0.63	34	
19-Sep-06	c4	230	6.6	0.71	35	
GPS	**mean**	**230**	**6.4**	**0.57**	**37**	**6.74%**
	median	**226**	**6.6**	**0.55**	**34**	
Cottonwood Creek - Traverse 2	c1	122	See note [left]	0.97	See note [left]	
normal	c2	160		2.64		
S 15-27 E	c3	174		1.85		
19-Sep-06	c4	224		2.14		
GPS	c5	168		2.28		
Note: GCRs have low heights, too subtle for	c6	99		2.16		
GPS precision	c7	239		1.22		
	c8	218		1.18		
	c9	242		0.95		
	c10	250		1.33		
	c11	192		1.44		
	c12	317		1.07		
	mean	**200**		**1.60**		**0.96%**
	median	**205**		**1.39**		
Cottonwood Creek - Traverse 3	c1	591	37.0	0.79	16	
reverse	c2	330	8.6	0.86	38	
S 23 E	c3	268	14.8	0.52	18	
19-Sep-06	c4	218		0.84		
GPS	c5	364	12.8	0.56	29	
	mean	**354**	**18.3**	**0.72**	**25**	**3.54%**
	median	**330**	**13.8**	**0.79**	**23**	
Cottonwood Creek - Traverse 4	c1	213	See note [left]	0.80	See note [left]	
reverse	c2	184		0.42		
S 26 E	c3	253		0.29		
19-Sep-06	**mean**	**216**		**0.50**		**7.09%**
GPS	**median**	**213**		**0.42**		
Note: GCRs have low heights, too subtle for GPS precision						
Total All GCRs	**133**					
	median	**250**	**8.6**	**-**	**29**	**-**

[a] traverse locations shown on map [Fig. 9]
[b] asymmetry = (length stoss side) / (length lee side)
[c] ripple index = wavelength / height
[d] GPS is WAAS-enabled

Table 4--Analysis of Wavelength to Determine Depth

Traverse	Type	Median Wave-length	Slope	DS**	Depth		Maximum Depth		
					calcu-lated	*if slope=.003*	High-stand	start of flow	end of flow
		ft	%	ft	ft	ft	ft	ft	ft
Cottonwood Cabin	normal	291	*1.2**	1.12	93	373	1310	710	240
Big GCRs	normal	462	1.2	1.78	144	593	1390	790	320
Pardee's Pit	normal	278	*1.0*	1.074	107	357	1410	810	340
Section 13	normal	230	*1.0*	0.89	89	295	1390	790	320
Section 24	normal	189	*1.0*	0.73	73	243	1410	810	340
Markle Pass	normal	122	0.7	0.47	65	157	1330	730	260
Cottonwood Ck 2	normal	205	1.0	0.79	83	263	1170	570	
Wills Ck Pass Antidunes	antidune	270	7.9	1.04	13	347	1110	510	40
Big Ck Pass Antidunes	antidune	224	4.0	0.86	21	288	1290	690	220
Markle Pass Antidunes	antidune	283	11.7	1.09	9	363	1120	520	50
Duck Pond Antidunes	antidune	333	11.7	1.28	11	427	890	290	
Cottonwood Ck 1	reverse	226	6.7	0.87	13	290	1090	490	
Cottonwood Ck 3	reverse	299	3.5	1.15	33	384	1170	570	
Cottonwood Ck 4	reverse	213	7.1	0.82	12	273	1250	650	

* *italic = estimated slope*

****** from **λ_μ = 393.5(DS)^0.66** [Baker, 1973]

Table 5--Analysis of Wavelength to Determine Velocity

Traverse	Type	Wavelength [ft]	Velocity [ft/sec] *	Velocity [m/sec] *
Cottonwood Cabin	normal	291	40.6	12.4
Big GCRs	normal	462	64.4	19.6
Pardee's Pit	normal	278	38.8	11.8
Section 13	normal	230	32.1	9.8
Section 24	normal	189	26.4	8.0
Markle Pass	normal	122	17.0	5.2
Cottonwood Ck 2	normal	205	28.6	8.7
Wills Ck Pass Antidunes	antidune	270	37.7	11.5
Big Ck Pass Antidunes	antidune	224	31.2	9.5
Markle Pass Antidunes	antidune	283	39.5	12.0
Duck Pond Antidunes	antidune	333	46.5	14.2
Cottonwood Ck 1	reverse	226	31.5	9.6
Cottonwood Ck 3	reverse	299	41.7	12.7
Cottonwood Ck 4	reverse	213	29.7	9.1

***** from **λ_μ = 8.24 V^0.870** [Baker, 1973]