Sternberg's Law Statistical Study of Surficial Gravels in North Central Montana—Part I: Methods and Findings

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Abstract

In the 150 years since Sternberg's Law of downstream fining was published, causes and complications have proliferated with research in many fluvial environments. The basic relationship is a first-order differential equation expressing an energy relationship, and the geologic causes and effects that fall under its umbrella are diverse. Grain size distributions of sands provide indications of modes of deposition, but gravels do not. However, while competence is seldom a limiting factor for sands, it is for gravels. The study area includes the low-relief Great Plains and the high relief of the Rocky Mountains. Island mountain ranges complicate this somewhat, but stream courses are sufficiently simple for Sternberg's Law. Most of the study area exhibits features generally believed to have resulted from Ice-Age glaciation. Catastrophic evidence in the form of planation surfaces is also present. Thus channelized flow, transport by ice, and sheet flow are all candidate processes for transport of gravel. Predictions of grain size distributions from these processes are compared with results from statistical analysis of 5,839 sieve analysis reports. The results indicate a complex history for the surficial gravel deposits.

Key Words: Central Montana, geostatistics, grain size distribution, gravel, paleohydrology, Sternberg's Law

Background

Gravel is one of the most important building materials in modern society, being the chief ingredient in concrete and the standard for structural fill to support buildings, roads, and other structures. It has therefore been researched for many years, with a wealth of data produced. Size-based terminology is shown in Table I, and terms that may be unfamiliar to some readers are included in the glossary.

While the stream power to transport fine sediments such as clay and silt is very low, coarse sediments require significant stream power. Laboratory

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Table I. Particle Sizes.

Category	Size (mm)		Size Description
Boulder	305 & up		melon and bigger
Cobble	76	305	baseball to melon
Pebble	4.76	76	pea to baseball
Sand	0.075	4.76	copy paper thick to pea size
Silt	0.002	0.075	1/3 size of red blood cell to thickness of one sheet copy paper
Clay	0.002 & down		1/3 size of red blood cell and smaller

Sizes per ASTM D2487; Wentworth Scale somewhat smaller.

research has centered on sand, and empirical equations have been developed to relate grain size and grain size distribution to current speed and stream power (Klevberg, 2019). Gravel is too large to be easily investigated in the laboratory, so most research is based on observed flood events. Since gravel requires greater stream power or current strength, i.e., *competence*, than sand and fines, it has been of special relevance to catastrophic versus

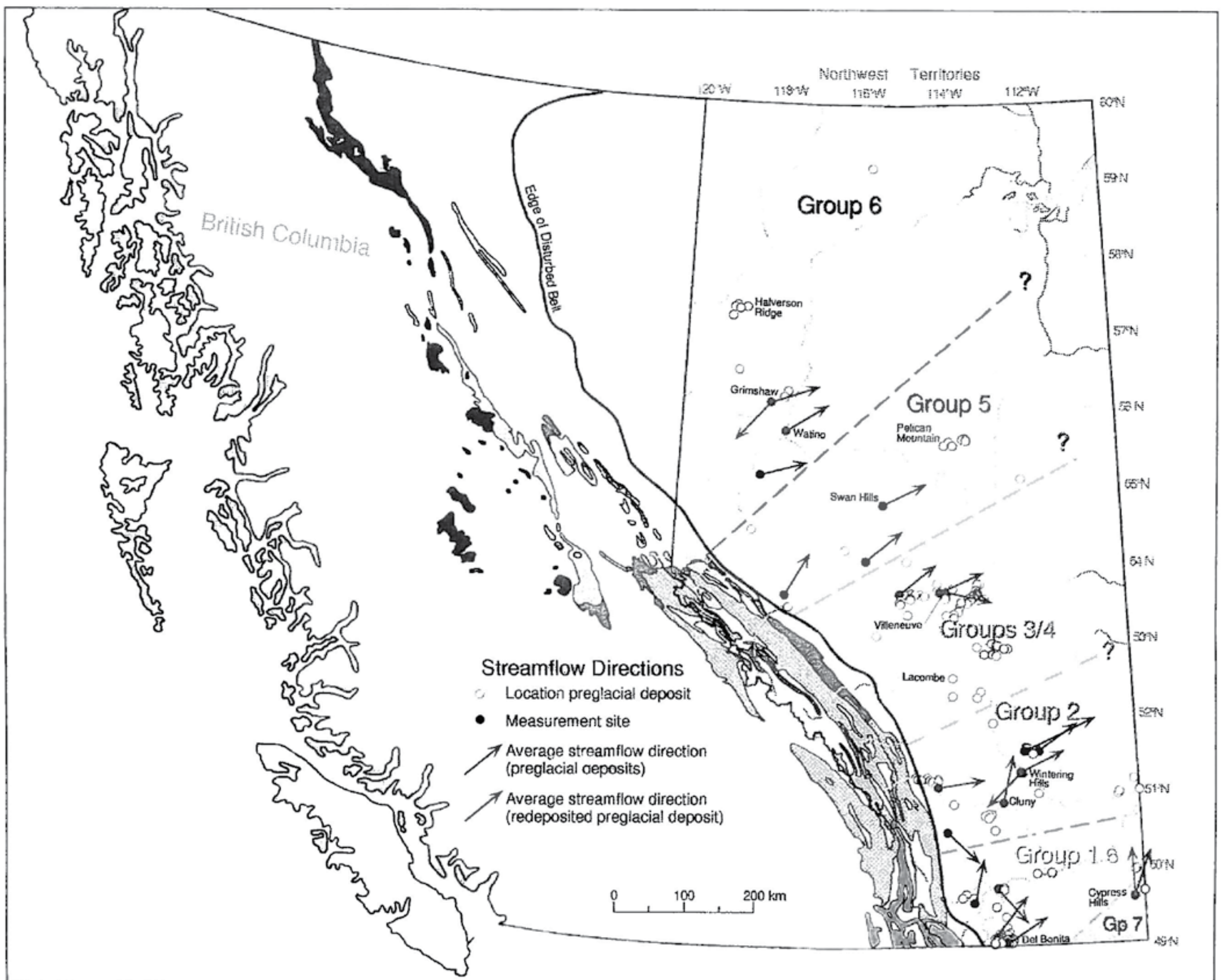


Figure 21. Average streamflow direction for preglacial deposits and redeposited preglacial deposits.

Figure 1. Figure 21 from Edwards and Scafe (1996). Slightly lighter gray arrows pointing back toward Rocky Mountains are inferred post-depositional paleocurrent directions which they interpret as redeposition of pre-glacial gravels. Slightly darker gray arrows pointing away from mountains are original flow directions inferred from lithologies identified in Rocky Mountains (shaded areas).

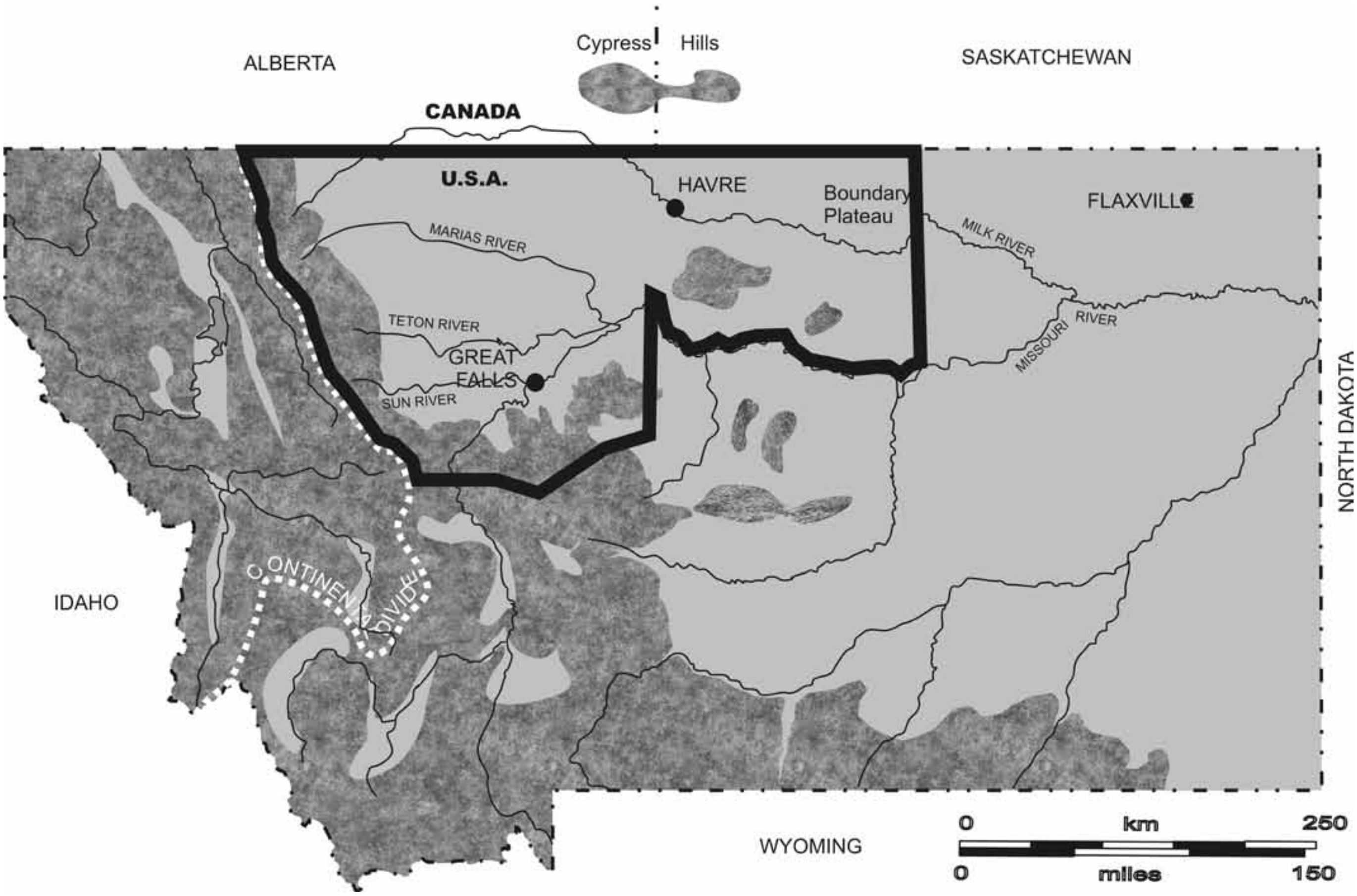


Figure 2. Study area in North Central Montana indicated by outline.

uniformitarian debates. Stream *capacity* relates to the total mass flux capacity of sediment and can be large even if competence is low. The Mississippi River is a fine example, "too thick to navigate, too thin to cultivate," carrying a heavy load of clay, silt, and fine sand but incapable of moving gravel.In addition to the paleohydrologic study of the Cypress Hills and Flaxville Formations by Klevberg and Oard (Klevberg and Oard, 1998; Oard and Klevberg, 1998), the Alberta Geological Survey has done extensive study of pre-glacial gravel deposits (Edwards and Scafe, 1996). They found it prohibitively expensive to run enough samples of statistically valid size (ASTM D75) to ascertain paleocurrent paths, so they relied on lithology as the primary criterion to trace provenance. They carefully excluded glacial deposits in their study, which required field observation and judgment. Source areas were quite consistently from the mountains to the southwest, though what is interpreted as glacial redeposition in the opposite direction was observed in some deposits (Figure 1). Apparently, no comparable study has been completed for Montana. Figure 2 shows our study area, which coincides with the Montana Department of Transportation (MDT) Great Falls and Havre Districts. The study area is approximately 250 miles (400 km) from west to east. It is dominated by a few major streams flowing quite consistently from west to east: the Milk, Marias, Teton, Sun, and Missouri Rivers (Figure 2). More than twenty years ago, we were assisted by Beverly Oard and Krista Koljonen, who photocopied thousands of sieve analysis reports from these MDT offices. Klevberg used a few of the data from the Boundary (Turner) Plateau (Figure 2) for hand calculations that indicated sheet deposition with current winnowing (Klevberg and Oard, 1998).An obstacle to further data analysis was the labor required to enter and statistically analyze the data. A Creation Research Society grant, breakeven hourly rates provided by TD&H Engineering, and the invaluable assistance of volunteers allowed us to complete the study. In

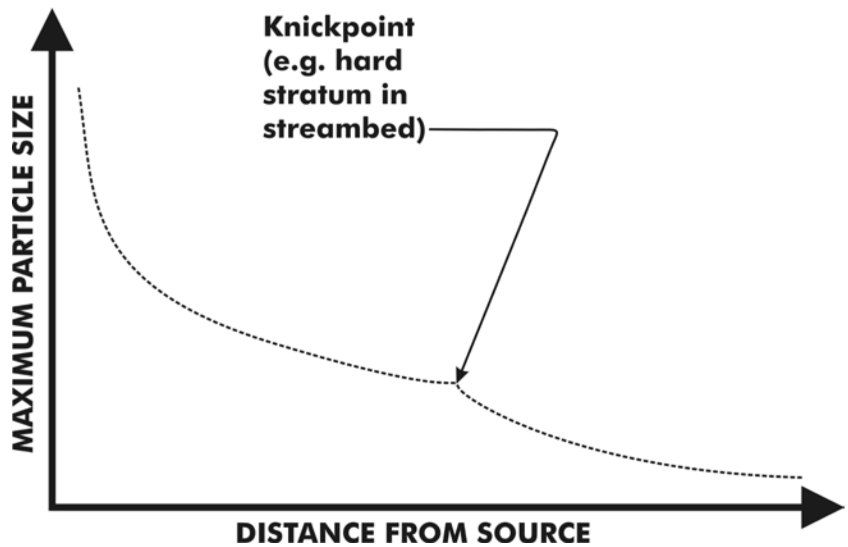


Figure 3. Schematic presentation of Sternberg's Law showing how size of particles (clasts) becomes smaller downstream. Abrupt changes in the mathematical description may occur at knickpoints (usually harder strata) or where tributaries enter the main stream.

the intervening years, technology has facilitated analysis of large datasets.

Sternberg's Law

This area of hydrologic research caught the attention of geologists long ago. Gravel is often observably smaller downstream, often of lithologies from the mountains and not the lowlands farther from the source. Sternberg (1875), in his famous study of the Rhine River, concluded abrasion was the cause of fining, while relative mobility has been shown in many more recent studies to be more important (Potter and Pettijohn, 1963; Pelletier, 1981; Hoey and Ferguson, 1997). However, the mathematical relationship is the same. Sternberg's Law expresses an obvious first-order relationship between potential energy and stream competence:

$$S = k\,\frac{dy}{dx}$$

where the term S is related to stream slope (hence velocity, power, and competence) via a constant k and the change in elevation above base level with distance downstream. Sternberg focused on diminution of a given particle (pebble) with distance downstream, expressed below in its original integral form:

$$W = W_0 e^{-aL}$$

where W is the weight of the largest observed pebble that has decreased from its initial weight exponentially over a distance L with a stream-specific constant *a*. The assumption is that a given pebble has lost this mass during transport.

Rates of transport and abrasion are both related to the stream power, in turn related to the height above base level. Sternberg's Law can be seen describing the conversion of potential energy to geologic work, by the first-order differential equation and resulting exponential stream profile, with concavity proportional to fining and decreasing over time. While abrasion can be a factor, the law applies even where fining is entirely due to sorting (Hoey and Ferguson, 1997; Brown, 2004). Sediment supply is an important variable. Fine sediment will produce a prograding wave that travels down the stream. Bed surface to subsurface sediment exchange takes place with finer sediment, but coarser sediments can become buried by advancing bedforms and removed from the transport process (Purkait, 2006). Fining is more rapid during higher discharges. Knickpoints (sudden changes in stream gradient, such as rapids or waterfalls) and other changes in stream geometry have obvious, complicating effects (Figure 3), as do stream networks. However, on the scale of a single reach, the relationship holds, and downstream-fining patterns are commonly discernable.

Development of Paleohydrology

Paleohydrology applies hydraulic principles to Earth history through physical data. While the results lack certainty, they are useful. For example, gravel on a particular topographic feature (paleoslope) can be used to calculate minimum current strength. Transport is inferred from lithology (different from substrate) and rounding of clasts. A transport hypothesis is disproven by field evidence showing an angular material identical to the substrate with only weathered joints between clasts. Transport in a shallow, meandering stream is likewise disproven by clasts that are too large to have been transported in such a stream.

Sternberg's Law was formulated for gravel, but also works for sand. Gravel and sand are large enough that electrostatic effects are negligible, and surface tension is also negligible for gravel. Silt and clay can have low

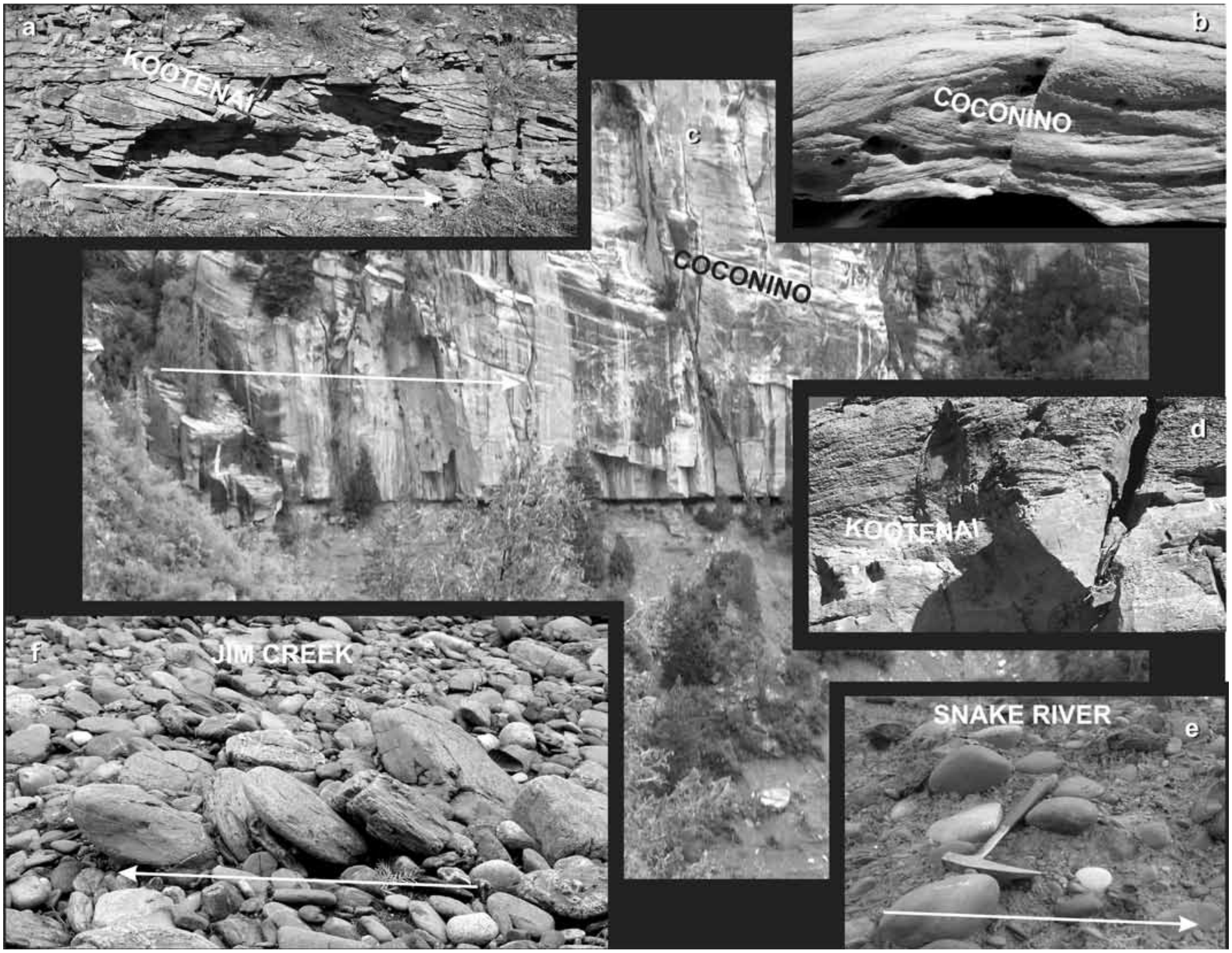


Figure 4. While there are many paleocurrent indicators–aligned fossils, sole markings, striations, asymmetric ripples, etc.–one of the main indicators for sandstones is cross-bedding. Upper four images show cross-bedded sandstones. Those at left are seen parallel to the paleocurrent direction as indicated by arrows. Those at right are oblique to the paleocurrent direction (no arrow). (a) lower Kootenai Formation, Sand Coulee, Montana. (b) close-up of Coconino Sandstone, Grand Canyon, Arizona. (c) Coconino outcrop in Grand Canyon. (d) Upper Kootenai Formation, Centerville, Montana. Lower two images are gravel, showing imbrication, which is the primary paleocurrent indicator for such coarse sediments. (e) deposit along Snake River in Idaho. (f) deposit in Jim Creek, Snohomish County, Washington. All photographs outside Montana, courtesy Michael J. Oard.

settling velocities, may flocculate, and boundary layer thickness may exceed particle diameter. Gravel typically rolls along the stream bottom as bed load, but sand may also move by saltation or even suspension. Fines (silt + clay) are usually transported as suspended load. Clay-size particles may require significantly higher current speeds to dislodge than to deposit, as they are cohesive. Thus, the finer the sediment, the more complex the transport typically becomes, and the mathematical description of the transport and depositional processes becomes less likely to conform to the simplified Sternberg expression. The finer sediments may be transported intermittently, sometimes settling between larger rocks that shelter them from currents. The smaller the particle, the more complex the depositional history may be. The flip side of this is that many more expressions that are of genetic significance have been derived for finer sediments than a simple Sternberg's Law description, including flow regime inferences from bedforms and various paleocurrent indicators (Figure 4). Most studies focus on sands rather than gravels. Sandstone is common in the rock record, and lower-energy environments today serve as convenient analogues (especially for those disinclined to consider high energy or catastrophic, depositional environments). High-energy environments are not so easily studied. Thus, environmental interpretations of grain-size statistics have been developed for sands, but not as much for gravels. Statistical methods are often employed for rivers, shorelines, and rock units in many settings with efforts made to separate alluvial from littoral genetic processes, for example, and various transport sequences (Passega, 1964; Sahu, 1964; Skaberne, 1996; Martins et al., 1997; Taj, 2011; Ganjoo and Kumar, 2012; Srivastava et al., 2012; Parthasarathy et al., 2016; Baiyegunhi et al., 2017). Evaluation of scatter plots of sorting versus skewness have been used for decades to distinguish depositional environments of sands (Friedman, 1961) and even finer-grained sediments (Diemer and Forsythe, 1995; Pinem and Muslim, 2019). Discriminant functions have been developed for sands, but not gravels (Madukwe, 2016; Rashed and Siad, 2016). Means of inferring transport mechanisms from sand grain-size distributions were pioneered in the salient work of Passega (1964).

On the other hand, gravel permits estimates of minimum stream competence. At least one study with a suitable reach of an extant gravel-bedded river has been performed (Hoey and Ferguson, 1997), and many attempted, but gravel-bedded rivers offer challenges and complexities that preclude application of Sternberg's Law on a small scale (Buffington and Montgomery, 1999; Evans and Holm-Denoma, 2018). Interestingly, it was this heterogeneity in gravel-bedded rivers and the differing requirements for suitable gravel for fish to host their eggs that prompted Kondolf and Wolman (1993) to formulate their grain-size analysis functions. In studies of seabed sediments along the coast of New England, Schlee (1973) extended the work of Passega to gravels, though inferred processes (e.g., continental glaciation) rather than only observed processes were included. Many individual streams have been studied per Sternberg's Law. Quantitative paleohydrologic analyses by creationists have produced salient results, such as Lalomov (2003) in Crimea and Barnhart's (2011) analysis of unconsolidated deposits from Hurricane Katrina and the Tapeats Sandstone (Barnhart, 2012a, 2012b). However, few areas exhibit *sheets* of gravel like Montana east of the Continental Divide. The Cypress Hills Formation and Flaxville Formation ("cypflax") deposits that blanket part of the study area for this research project (Figure 5a) differ significantly from ordinary fluvial deposits (Klevberg and Oard, 1998; Oard and Klevberg, 1998). Surficial gravel deposits extend into Canada, and extensive research has been conducted in Alberta (Edwards and Scafe, 1996). This study addresses an apparent lack of such research in Montana and includes the sheet gravels.

Mystery of Bench Gravels

Montana east of the Continental Divide (Figure 2) presents a useful topographic contrast for paleohydrology. The rugged Rocky Mountains abruptly face the Great Plains. Other than a few isolated or "island" mountain ranges that pop out of the prairie away from other mountains (stippled gray in Figure 2) and a few prominent river valleys, the Great Plains is comprised of rather flat "benches" carved into soft sedimentary rocks that ramp into each other and are often mantled by gravel of very hard lithologies. These are commonly labeled "braid plain deposits" by uniformitarians (Vuke et al., 2002, 2007), but their architecture does not match the expected patchwork of lag gravels and sands of anastomosing streams (Evans and Holm-Denoma, 2018). Most economical gravel deposits are from these bench gravels, though some pits mine glacial gravels, and a few operate in valley bottom alluvium.

Gravel deposits capping the Cypress Hills and Flaxville Plain in Montana, Alberta, and Saskatchewan (Figure 5) defy uniformitarian explanation and are better explained by late diluvial deposition (Klevberg and Oard, 1998; Oard and Klevberg, 1998, 2005; Oard et al. 2005a, 2005b, 2006). Paleocurrent indicators include imbrication and cross-bedding (Figure 4). Clasts are well rounded and covered with percussion marks (Figure 5b). Deposits are in sheet form and cover the high planation surfaces *above* the level of glaciation. Work performed by Klevberg and Oard was almost entirely a *competence* study. While some analysis was included of grain-size statistics showing current winnowing indicative of regional rather than fluvial currents, no *capacity* analysis was included, and no additional statistical analysis was pursued.

Forensic Methods

Klevberg and Oard (1998) argued for sheet flow rather than channelized flow for the "cypflax" deposits, based on many observations of individual clasts, deposit architecture, and their mapped and observed lateral extent. Minimum current speed was derived from maximum clast size and open channel equations, and current depth was inferred from paleoslope and minimum current speed. Staff of the Montana Bureau of Mines and Geology believe that these deposits can

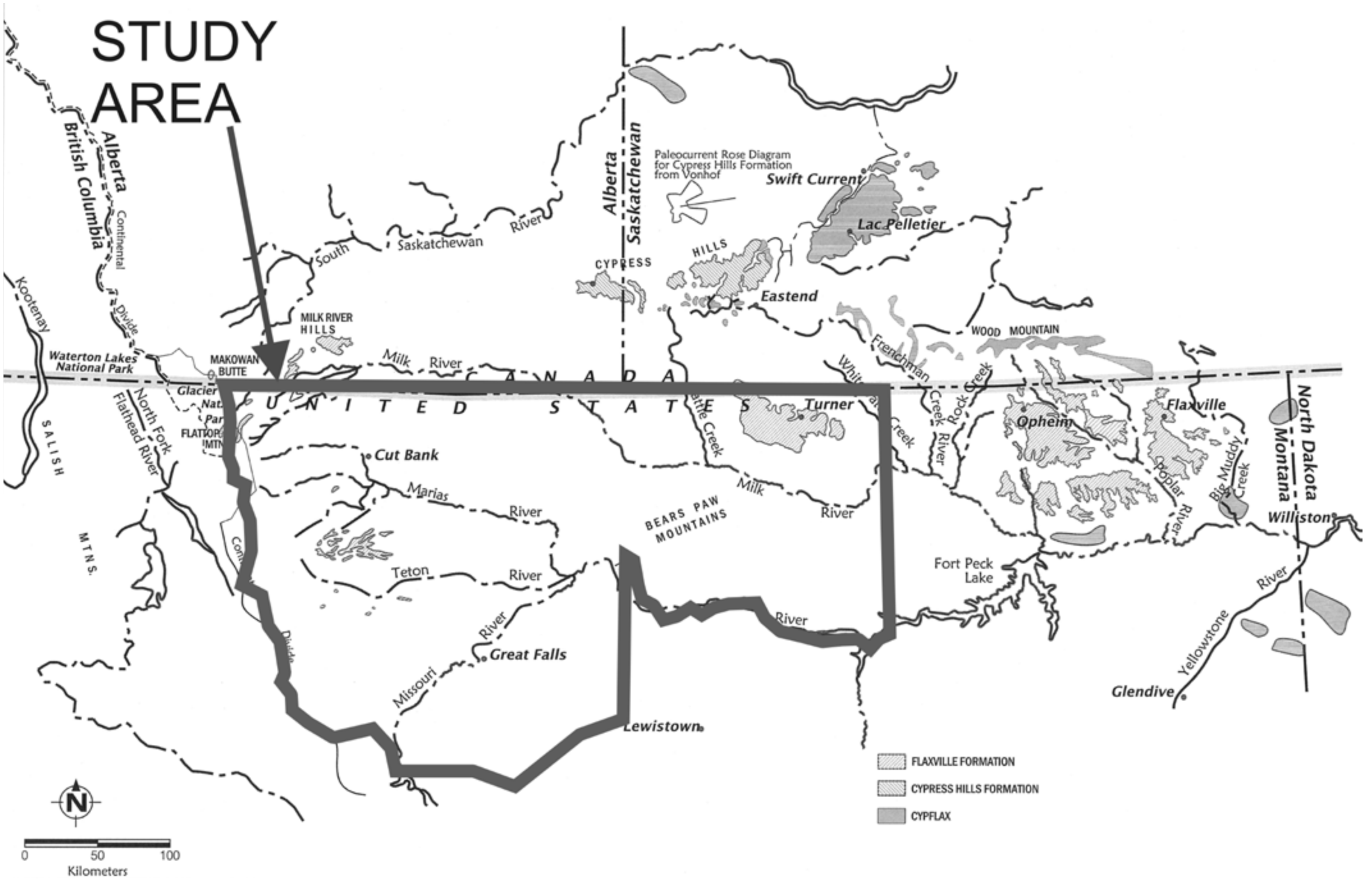
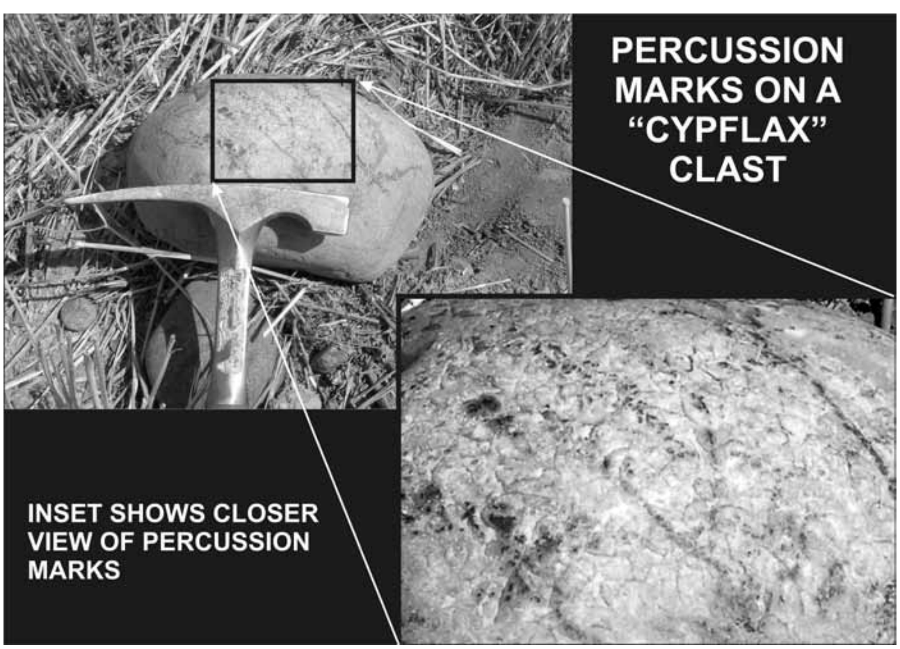


Figure 5. (a) ***(above)*** **Map showing Cypress Hills Formation and Flaxville Formation deposits on erosional remnants in Montana, Alberta, and Saskatchewan. These appear to grade into each other with equivocal deposits (labelled simply "cypflax"). Rose diagram on figure north of Cypress Hills is based primarily on crossbeds in sand interbeds. (b)** ***(below)*** **photograph of "cypflax" cobble with close-up of percussion marks. Stripes are rust streaks from farm implements scraping over cobble.**



be explained by lateral accretion with gradual downcutting to form a very low slope perpendicular to the flow direction. While this seems farfetched (Klevberg and Oard, 1998), more work could be done to further define depositional environments and discard hypotheses that are not feasible. This research is an initial step.

Natural history is *history*, not science (Reed and Klevberg, 2014a, 2014b), but science plays an essential forensic role. Predictions of hypotheses can be identified, and these predictions tested by present observations. This procedure was demonstrated in Klevberg and Oard (1998) and is used in this study.

Creationists acknowledge that non-diluvial geologic processes, such as continental glaciation, contribute to the present form of surficial deposits. There are various ways to distinguish these in the field, but many are subjective, influenced by natural-history paradigms. This project minimized subjectivity by statistically analyzing a large, semi-random sample population, and using those results to test predictions of possible genetic mechanisms. Sternberg's Law is a one-dimensional representation of fining along a stream channel (Figure 6). As shown in Figure 7, this research project extended analysis to two dimensions

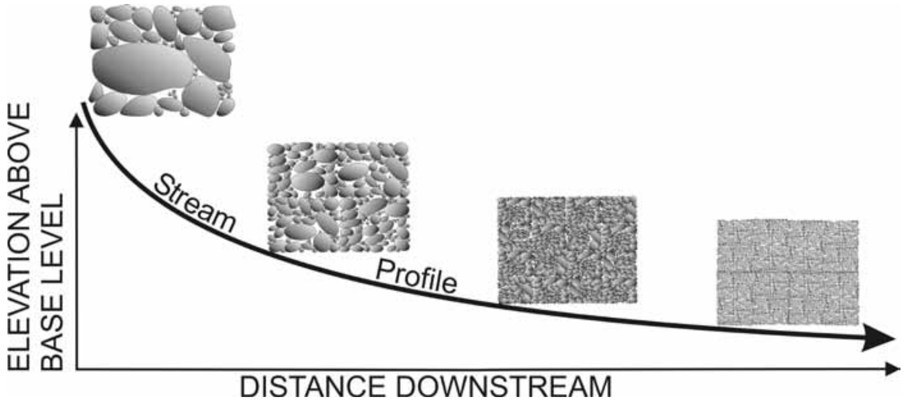


Figure 6. Schematic representation of Sternberg's Law in terms of elevation above base level showing how both fineness and rounding increases downstream.

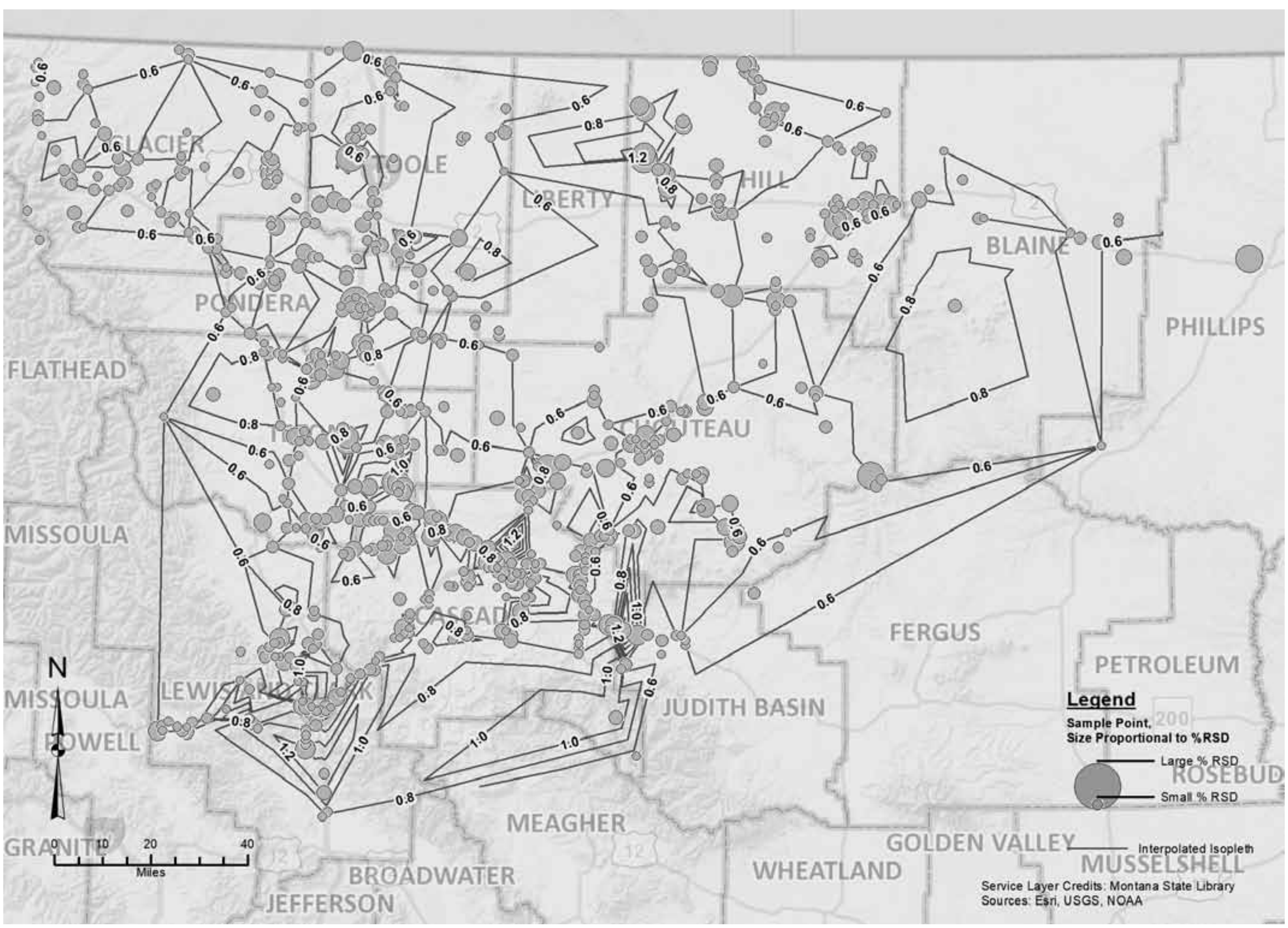


Figure 7. Map of study area generated from project data using global information system (GIS) with isopleths of kurtosis calculated using Inman (1952) functions.

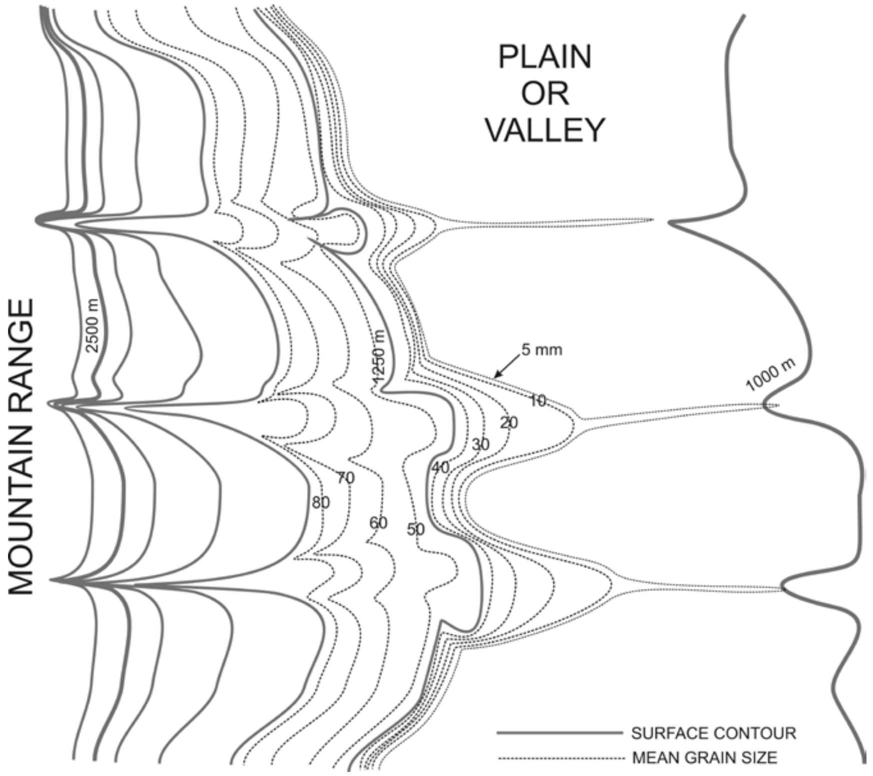


Figure 8. Idealized map showing ground surface contours (solid lines) and mean grain size isopleths (dashed lines) to illustrate how streams emanating from mountain front transport larger clasts greater distances than are transported onto interfluves.

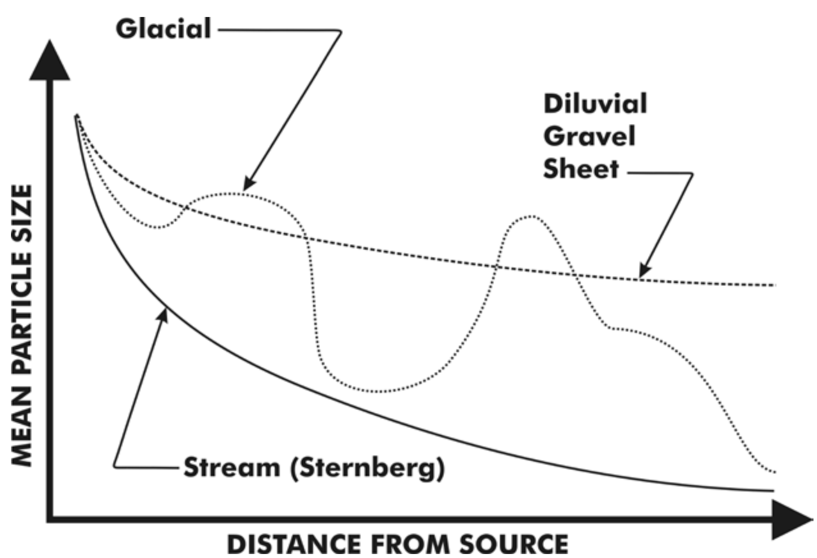


Figure 9. Predictions of depositional processes on Sternberg plot. Diluvial deposition would mimic fluvial deposition on a large scale and show more gradual downstream fining, thanks to large, powerful currents. Glacial transport would show a general trend to drop larger boulders from ice, with many irregularities in deposition (e.g., till).

(thickness is negligible at this scale) in order to indicate possible gravel sources and paleocurrent directions. The approach was:

1. List predictions of different depositional hypotheses.
2. Develop maps showing actual grain-size patterns using standard grain size distribution statistics.
3. Test predictions by data.

Stream channels flowing from the Rocky Mountains should show a strong Sternberg's Law behavior from west-southwest to east-northeast, with no correlation north and south, since eastward fining would occur at different rates in different streams (Figure 8). A simplified diagram of this prediction of downstream fining is shown in Figure 3. Sheet deposition should show greater uniformity and might not show the rapid downstream fining of modern streams. Glacial deposits should form isolated, short segments near the Continental Divide and farther out on the plains, trending northwest to southeast but otherwise patternless. Figure 9 compares these predictions relative to a Sternberg fining curve (Figure 3).

Statistical Methods

Statistical evaluation of coarse sediment transport focuses on the median or b-axis of each clast. Some geologists record only the long, a-axis, but the b-axis determines the bed shear stress to be overcome for the clast to begin rolling as bed load. This dimension also determines whether the clast will pass through the mesh of a given sieve. This is fortuitous, as the dimension measured by sieve analysis is that of interest for paleohydrology.

Previous studies have noted the need for: (1) large sets of data, and (2) individual samples large enough to be representative of larger clasts (ASTM D75; Koch and Link, 1980; Edwards and Scafe, 1996). Collecting and analyzing such samples is laborious, but the process has proceeded for many years as MDT has looked for aggregate sources for road projects. The author's initial estimate of a minimum population for a meaningful signal-to-noise ratio for this study was 1,500 samples. Data for a total of 5,839 samples representing 699 gravel pits or sampling locations were entered.

Potential Sources of Error

Several potential sources of error were identified and addressed, as possible: data entry errors, nonrandom selection of gravel pits, inclusion of results for processed material and binder, interpolation/extrapolation errors in producing grain size distribution curves, small sieve stacks and heavy tails, omission of oversize, and geographic rounding errors. Data entry errors could originate from mistakes on laboratory sheets, errors when the original reports were typed up, and errors when those reports were entered into the spreadsheet. Site sampling was not truly random. "High grading" was practiced; good gravel deposits were sought out, and areas barren of gravel were ignored. Where gravel was plentiful, sites near roads were commonly selected. In a few cases, the samples were not pit run gravel, but were stockpiled materials, sometimes crushed and screened. Oversized material was sometimes ignored since the objective of sampling was to locate suitable mine sites for obtaining construction material rather than simply doing geologic research. For the same reason, sieve stacks were often too short, i.e., sieves were based on required material properties, which resulted in some uncertainties in the actual particle distribution curve. Once the laboratory results were input into the spreadsheet, these "missing sieves" were interpolated and in a few cases extrapolated. The site locations were based on legal descriptions and only determined to the nearest section. The potential error in location is the width of a section, i.e., one mile (1.6 km).Some pits had many samples, others few. Those with more samples would result in a smaller relative standard deviation (RSD). The dots representing individual pits on maps were scaled to match the RSD values: large numbers of samples resulted in small RSD values and small dots on the maps. A problem arose with isolated samples where the standard deviation was undefined, so these were arbitrarily assigned larger RSD values (i.e., larger dots on the maps). This allows a visual assessment of data quality while not obscuring contouring. I have judged that variations in values represented by RSD are random and negligible in magnitude compared with distances between sampling locations.

Reducing Error

Original errors on laboratory data sheets are unknown but probably few, since construction materials testing laboratory supervisors usually proofread them before reports are generated. This study's spreadsheet was programmed to detect data entry errors from the original typing and those that occurred when the data were entered into the spreadsheet. Since it is impossible for the cumulative percent passing through a smaller sieve to exceed that of a larger sieve, any sample where numbers indicated this occurred was flagged. Each was then examined, and in most cases corrected; the error was usually an obvious transposition or misreading of low-fidelity copy. While site sampling was not truly geographically random, the number and distribution of samples was sufficiently so with a few exceptions. Few pits were sampled in mountainous areas, and Liberty County is poorly represented. The mountaintops are inconsequential to a Sternberg's Law analysis; however, the Liberty gap (i.e., lack of results for Liberty County) could influence results. It can later be filled in; it was only due to exhausting the budget to photocopy reports there. The Boundary Plateau (or Turner Plateau) was also omitted (Figure 2). "High grading" is deemed of little consequence since the gravel that attracted MDT samplers was the subject of this investigation. However, good gravel deposits may locally be mantled by fine-grained soils, one of the vagaries of geologic investigation in general, and perhaps best dealt with by large sample populations. A conditional statement was included in the spreadsheet to detect samples with curves not typical of gravel (typically far more uniform), and a few cases of processed material were identified and excluded. Omitted, oversized material in reports was more problematic, as maximum clast-size defines minimum paleocurrent competence.

A more conservative approach of using the D_{95} value was therefore followed instead of using largest clast or D_{99} (D_n refers to the diameter at which n percent of the mass of the sample is finer). Interpolated D_n values were tested in the same way as data entry errors were detected, and a few random samples were also checked using hand calculations and by entering the data into Geosystem software, the laboratory package used by TD&H Engineering to generate gradation reports. Samples with these detected errors were not analyzed. These numbered 204, leaving 5,635 samples for analysis. The maximum potential location error of one mile is 0.4% of the width of the study area and deemed inconsequential. More significant location errors were flagged, and hard copies examined. Common errors were in direction (e.g., labeling a range 13W instead of 13E, an error of 156 miles).

Table II. Equations for Gravel Statistics.

Authors→	Inman	Kondolf and Wolman	Trask	Folk and Ward
Type	Arithmetic	Geometric	Mixed	Geometric-Inclusive
Median	φ_{50}	D_{50}	D_{50}	φ_{50}
Mean	$(\varphi_{16}+\varphi_{84})/2$	$(D_{16}+D_{84})^{0.5}$	$(D_{25}+D_{75})/2$	$(\varphi_{16}+\varphi_{50}+\varphi_{84})/3$
Sorting	$(\varphi_{84}-\varphi_{16})/2$	$(D_{16}/D_{84})^{0.5}$	$(D_{25}/D_{75})^{0.5}$	$(\varphi_{84}-\varphi_{16})/4+(\varphi_{95}-\varphi_{5})/6.6$
Skewness	$(\varphi_{5}-\varphi_{95})/(\varphi_{84}-\varphi_{16})/2$	$((D_{16}*D_{84})/(D_{75}/D_{25}))^{-0.5}$	$(D_{25}*D_{75})/(D_{50}{}^{2})$	$(\varphi_{84}+\varphi_{16}-2\varphi_{50})/(2(\varphi_{84}-\varphi_{16}))+$ $(\varphi_{95+}\varphi_{5}-2\varphi_{50})/(2(\varphi_{5+}\varphi_{95}))$
Kurtosis	$(((\varphi95-\varphi5)/2)-((\varphi84-\varphi16))/2)/$ $((\varphi_{84}-\varphi_{16})/2)$	$((D_{16}/D_{84})/(D_{75}/D_{25}))^{0.5}$	$(D_{75}-D_{25})/$ $(2*(D_{90}-D_{10}))$	$(\varphi_{95}-\varphi_{5})/(2.44(\varphi_{75}-\varphi_{25}))$

Computations

Automated methods proved more troublesome and error prone than simply entering all the data by hand. Data were loaded into an Excel spreadsheet with routines written in Visual Basic. While a database program would have been more elegant, Excel was familiar and readily available. A sixth-order polynomial was fitted to the data in order to determine the following parameters: D_{100}, D_{95}, D_{87}, etc., measured on the b-axis. Extrapolation was required for material retained on the largest sieve and where a value of more than 10% fines (clay + silt) was present. The polynomial was constrained to prevent local maxima or minima (physically impossible). Interpolation was required for necessary intermediate values needed to calculate statistical parameters. Once all the D_n values had been obtained to fill out that part of the spreadsheet, statistical values were generated per Table II. Four common methods are shown in Table II (Trask, 1932; Inman, 1952; Folk and Ward, 1957; Kondolf and Wolman, 1993). These differences largely revolve around the assumptions of normal or log normal population distribution and how the actual population differs from these assumptions. The Trask definitions are the earliest, simplest, and widely used for petroleum geology in sandstone reservoirs. The Kondolf and Wolman definitions are heavily weighted to tails since they were developed to evaluate gravel river beds for salmonid spawning potential. Folk and Ward (1957) are probably the most widely used in sedimentation studies as they address both tails and central distribution. Legal descriptions of the sample locations were used to create a GIS base map and a series of isopleth ("equal quantity") maps showing contoured statistical values. The three different hypotheses for gravel deposition compared in this study predict distinct patterns that can be visually compared with the actual patterns. The uniformitarian fluvial hypothesis predicts patterns for each stream particular to it, that are closely spaced near the mountains and more widely spaced on the plains per Sternberg's Law (Figure 8). Sternberg's Law also applies to some modern braid plains (Browne, 2004). Mountain "islands" (or "island mountains") complicate the pattern, and extensive bench gravels attributed to braided streams are accommodated by Figure 10.

Working Hypotheses

Various transport mechanisms can be envisioned, from the mundane to the outlandish. These have been addressed in greater detail previously (Klevberg and Oard, 1998). Discounting various unobserved and imaginative mechanisms, and acknowledging there is always the possibility of something not yet thought of, there remain four broad mechanisms for sediment transport: mass wasting, ice, water, and wind. Mass wasting may occur subaerially or subaqueously. Ice may transport sediment beneath the ice, within the ice, or on the ice, often in association with water. Transport in water may be channelized, sheet flow, or cyclic, occurring in fluvial, diluvial, lacustrine, or marine environments. Wind applies only to subaerial transport of particles small enough to be moved by the low density fluid that is air.

Mass wasting is readily discounted at this scale, and wind does not transport gravel. Evidence for both cordilleran and continental glacial transport is found as widespread diamict (glacial till), angular rocks from distant sources, and erratic boulders. The area believed to have been glaciated (Fullerton et al., 2004) covers most of the study area,

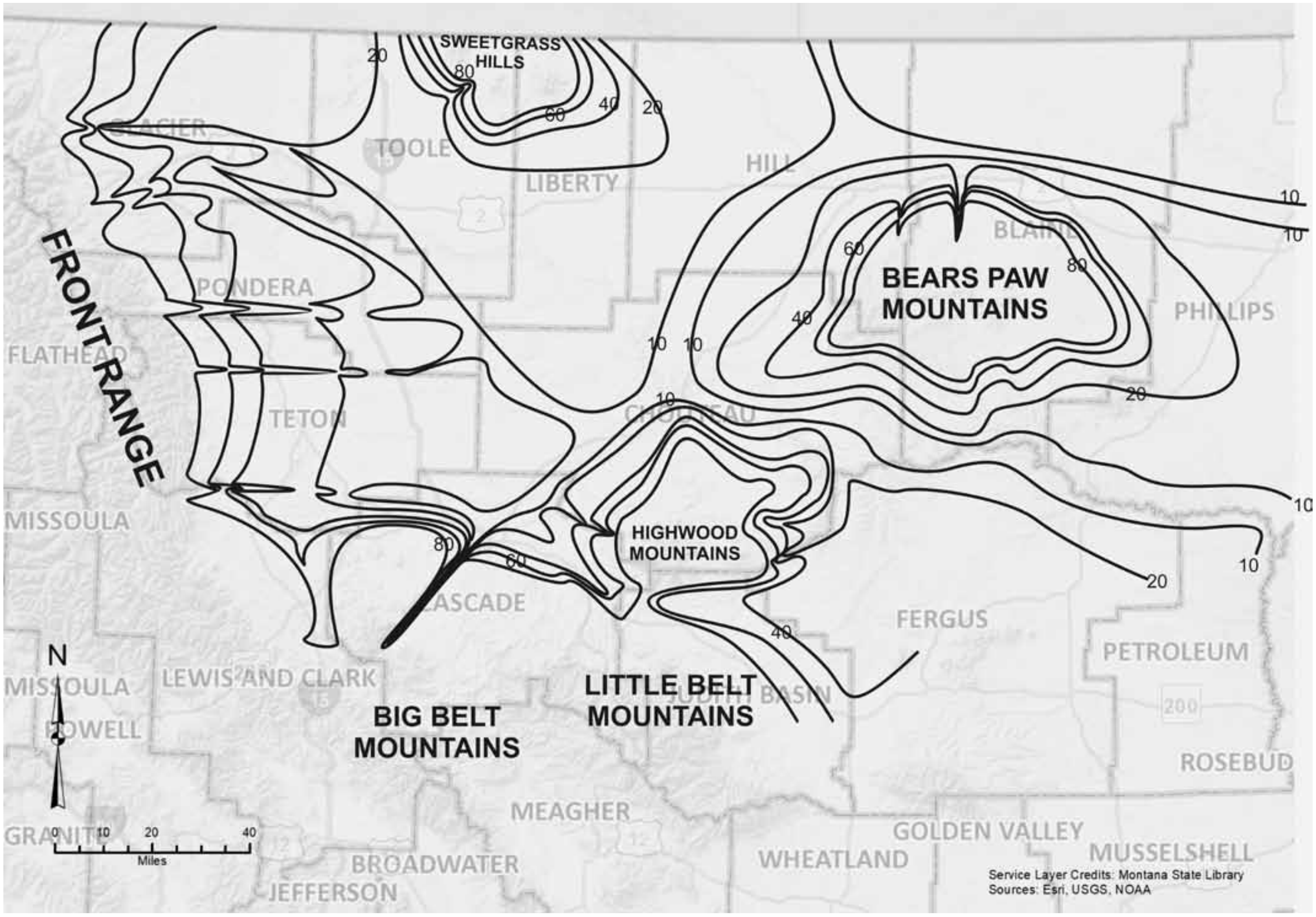


Figure 10. The influence of mountain ranges and the presence of gravel-capped benches traditionally interpreted as "braid plains" are incorporated into this figure of the study area, significantly modifying the idealized situation shown in Figure 8.

except that southeast of the Missouri River (Figure 2). There is evidence for water transport across the study area—rounded clasts, stratification, sorting, cross-bedding, and imbrication. These are predicted by both the fluvial and diluvial (sheet flow) hypotheses. Although grain-size variations have been used in marine settings (Diemer and Forsythe, 1995), neither the fluvial nor diluvial hypotheses predicts that setting. Marine processes such as turbidity currents are lumped under the general term "diluvial" here. Diluvial sheet deposition could create a simple pattern (Figure 11), but it would be complicated by topography, especially as flow became shallower and more channelized. Genesis 8 indicates assuaging of Floodwaters receded over a period of months. Eventually, decreasing flow in developing channels would approximate Sternberg's Law.

Findings

The significance of the computed statistics is shown in Table III. These statistics were mapped for the methods included in Table II, though most of the figures generated are not shown, due to space considerations.

Patterns

Maximum particle size (approximated by D_{95}) decreases from the mountain front toward the Great Plains (Figure 12). The pattern is not as clear for mean size, but the Trask mean (see Table II) generally diminishes from 10–20 mm at the mountain front to 5–15 mm at the east end of the study area (Figure 13). The mean values for the other three methods display a similar relationship.

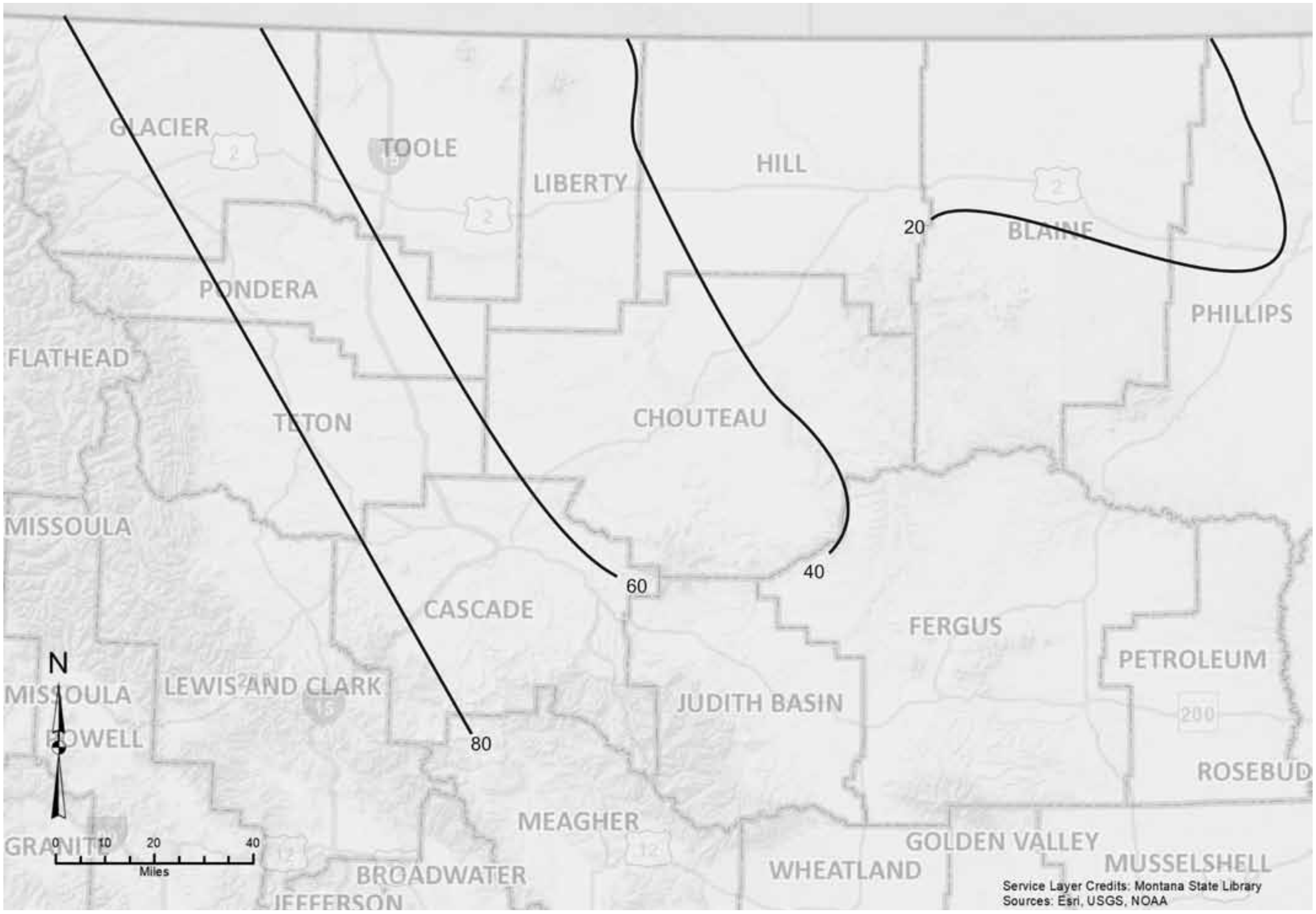


Figure 11. As shown in Figure 9, diluvial transport could be expected to "stretch out" the downstream fining and erase the interfluves that produce the pattern in Figure 8. The simple pattern shown here would be greatly affected by the obstructions created by mountain ranges.

Effects from the mountain ranges are imprinted on the general fining-eastward trend.

Sorting

Sorting is a fundamental statistic. It is the standard deviation of the population and the inverse of grading, e.g., a poorly-sorted sediment is a well-graded sediment, with a wide range of particle sizes. It often forms a clear Sternberg's relationship downstream (Figure 14) that points to origin. McLaren (1981) noted at least three cases (Table IV). Erosion, transport, and deposition may be repeated, with the sedimentary deposit of one event becoming the source for the next. Taking the limit of this function results in Case IV. As McLaren (1981) showed, sorting always improves with transport. Incorporation of bedload (Case IV) changes this situation, though as the current wanes, Cases I–III again apply. The importance of waning current effects was pointed out by Unde and Dhakal (2009) where mixed clay and gravel deposits were observed to form in backwater eddies.

Figures 14–16 show the relationship (or lack thereof) between mean size and sorting. Note the very low coefficient of determination (r^2) of the linear fit to the data in Figure 16. Various scenarios could explain this:

- Transport from a given source is not reflected in the data, i.e., they are unrelated deposits.
- Transport from a given source is reflected in the data but not the source itself, i.e., they are similarly deposited ("all at once").
- A significant portion of the data resulted from Case IV.
- Glacial transport was involved; ice was too viscous for sorting to occur.

Table III. Significance of Gravel Statistics.

Parameter	Definition	Significance
D_{100}	Minimum b-axis for which 100% of sample mass is finer.	Current strength minimum determined from D_{100} and paleoslope.
D_{95}	Minimum b-axis for which 95% of sample mass is finer.	More conservative for current strength estimation by eliminating outliers.
D_{50}	Minimum b-axis for which 50% of sample mass is finer.	Median. Primarily useful in computing other statistics.
Coefficent of Uniformity	Particle size distribution curve shape parameter: $D_{60}/D_{10.}$	Needed for classifying soil as well-graded (poorly sorted) or poorly-graded (well sorted).
Coefficient of Curvature	Particle size distribution curve shape parameter: $D_{30}{}^2/(D_{60} \bullet D_{10})$.	Needed for classifying soil as well-graded or poorly-graded per ASTM D2487.
Median	D_{50} or $\varphi_{50.}$	D_{50} value in millimeters; phi value (φ_{50}) is $-\log_2(D_{50})$
Mean	Lognormal, mass-based, variously defined (see Table II).	Average grain size based on sample mass. Useful in determining capacity but not competancy of stream.
Sorting	Lognormal, mass-based, variously defined (see Table II)—standard deviation.	Variation in grain size. High values mean poorly sorted. Sorting is typically effect of transport distance wherein smaller particles move faster downstream and reduce the range of particle sizes at a given location.
Skewness	Asymmetry of probability distribution, variously defined (see Table II)—third moment (geometric definitions).	Symmetry of distribution. Positive skewness means weighted toward fine grains, negative means coarse grains.
Kurtosis	«Tailedness» of probability distribution, variously defined (see Table II)—fourth moment (geometric definitions).	Degree of sorting of middle portion of distribution versus coarse and fine tails. Leptokurtic distributions are better sorted in middle than ends («peaky», k>1), while platykurtic distributions are better sorted in tails and «flat peaked» (k<1). Values near 1.0 are mesokurtic.

Skewness

Skewness is more equivocal (Figure 17; cp. Figure 18). As shown in Table IV, positive skewness coincides with Cases II–IV and is not diagnostic. The relationship between mean and skewness (Figure 19) shows the r^2 is an insignificant 0.0313. The aforementioned scenarios explaining sorting could explain skewness.

Kurtosis

High kurtosis values (i.e., those clustered at the tails and peak around the mean) indicate many outliers or tails relative to the middle sizes. An example of kurtosis results is Figure 7. While there are not marked differences between kurtosis plots using the four methods, there are some minor ones. Kurtosis is generally higher away from the mountains and in the canyons of the Missouri River. A material that would produce relatively high kurtosis (and positive skewness) is seen in Figure 20. Note the considerable sand matrix in well sorted gravel.

Scatter Plots

Figure 21 shows the project data with a linear regression. The r^2 value is 0.018, which is evidence of noisy data or dubious correlation. Figure 22 includes a portion of these data along with relationships for sand bodies in various modern environments. While skewed slightly to the negative (coarse) side, positive skewness is nearly as common. This could be explained by a mixture of Case I and the other cases per Table IV.

C-M Diagram

A C-M diagram displays the D_{99} value (C) versus the D_{50} value (M). M is the abscissa, while C is the ordinate. Figure 23 shows the project data compared to observed depositional processes. Note that D_{95} values were substituted for D_{99}

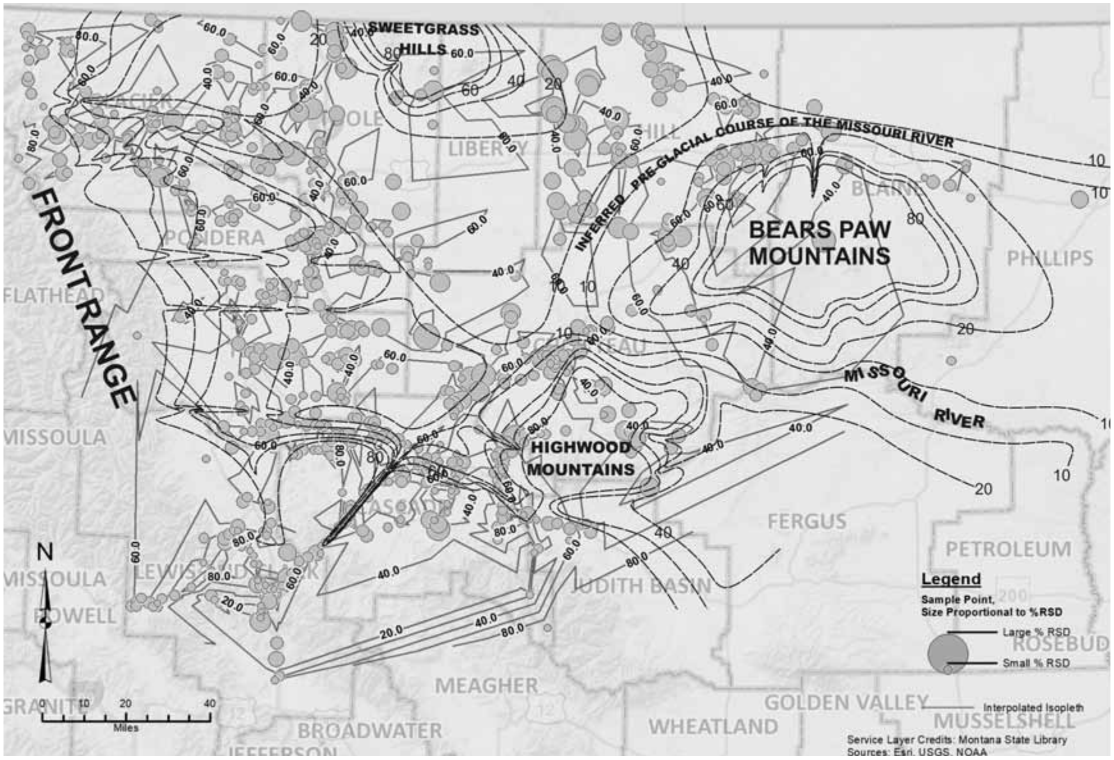
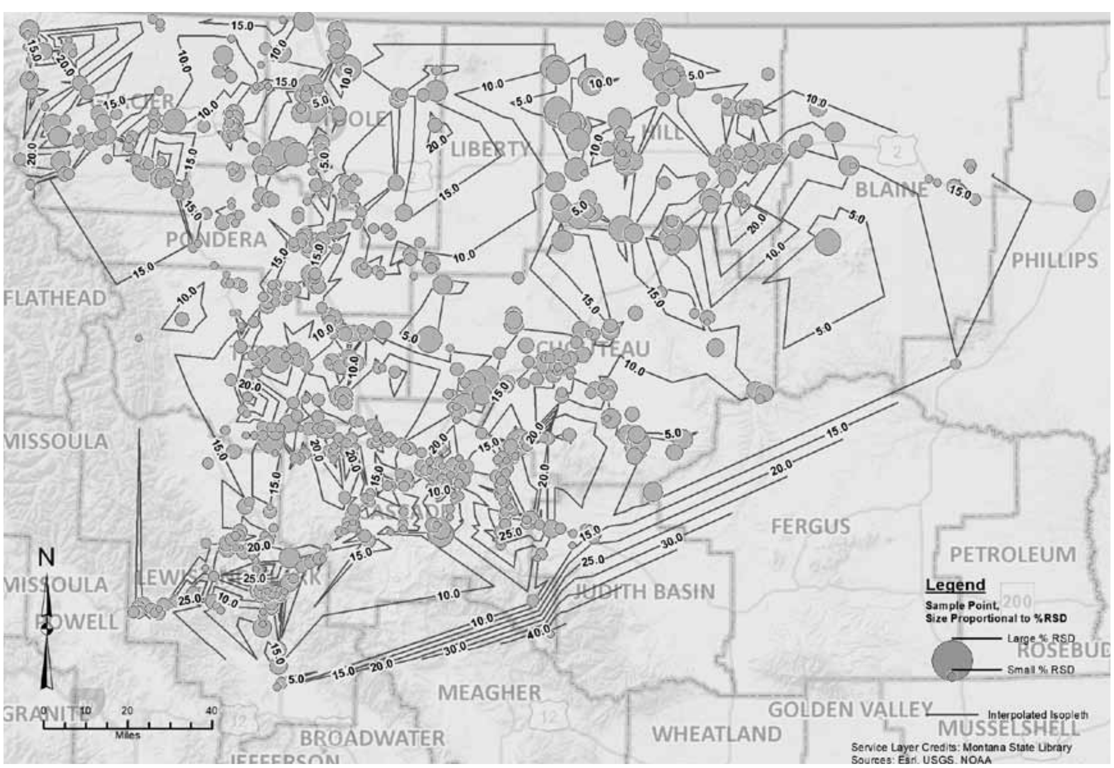


Figure 12 ***(above)*****. Isopleth map of 95th percentile of clast size superimposed on Figure 10. Dashed lines are isopleths from project data; solid lines are predicted isopleths based on Sternberg's Law. Note that while there is considerable discordance between the two, there is some localized similarity, and there is a definite fining from west-southwest to east-northeast across the study area.**

Figure 13 ***(below)*****. GIS-generated map of Trask (1932) mean. Fining from mountain front onto prairie is evident, but no clear pattern in the data corresponding to modern streams.**



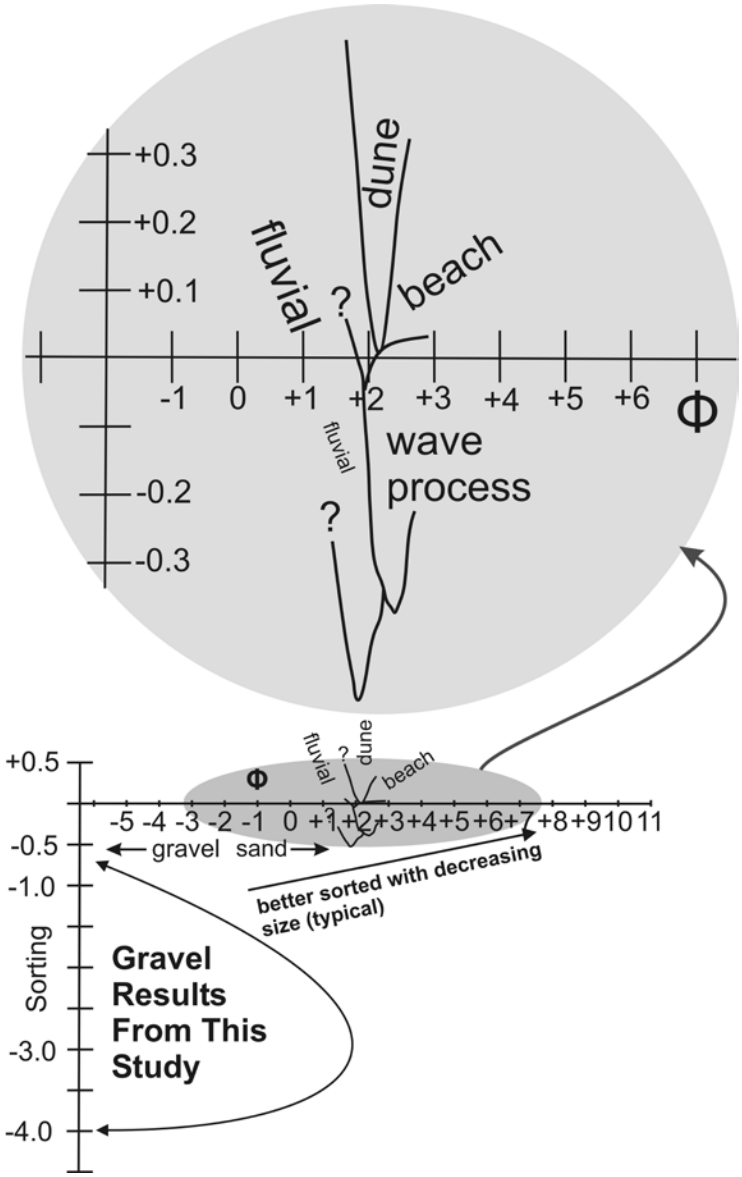


Figure 14. Particle size in phi units versus sorting coefficient showing transport process domains per Passega (1964) and others in the sand range (right side of figure) and a parabola tracing the edge of gravel data from this study (left side of figure). Arrow shows expected increase in sorting with decrease in size resulting from sorting action of current.

values as described above. The data would plot somewhat higher with reliable D_{99} values, though the difference might not be perceptible at this scale. Note the preponderance of data with C-M values coinciding with modern river terrace and beach deposits.

Conclusions

Methods:

1. Sternberg's Law is a first-order differential equation reflecting the relationship between geologic work and potential energy. It works for a variety of particle sizes and diminution mechanisms.
2. Unlike smaller particle sizes, gravel permits paleohydrologic calculations of minimum stream (i.e., current) competence.
3 The study area is highly appropriate for a Sternberg's Law analysis due to the large area of marked relief between the Rocky Mountains and the Great Plains.
4. Sheets of gravel composed of exotic lithologies cover most of the benches (Great Plains outside river valleys); this differs significantly from the typical fluvial environment that is the subject of nearly all Sternberg's Law studies. They all lack the expected architecture for braid plains. However, sheetflow deposition should also follow Sternberg's Law as the same relation of energy and work applies.
5. Predictions of hypotheses can be identified and compared with observations both statistically and graphically.
6. The final data set achieved the goals of the project for population size and precision. The minimum estimated population size to achieve desired accuracy and precision was 1,500. The final spreadsheet contained a total of 5,839 samples.

Conclusions:

7. Mapping revealed a general Sternberg's relationship, fining eastward though interrupted by "island mountains." However, the relationship is not strong as shown by many crossing lines of predicted and observed values.
8. There is very little correlation between sorting and mean grain size. This could result from transport from unrelated deposits, mixed deposition from a sudden drop in current strength, material eroded by a current with excess capacity, or glacial transport.

Table IV. Effects of Transport Sequence (after McLaren, 1981).

Case	Process	Mean	Sorting	Skewness
I	Erosion incapable of removing largest clasts from source, transport, total deposition	smaller	better	negative
	Erosion capable of removing all clasts, segregation in transport, total deposition following lag deposition (segregation)			
II	Erosion incapable of removing largest clasts from source, then lag deposition	coarser	better	positive
	Erosion capable of removing all clasts, then lag deposition			
IIIA	Erosion incapable of removing largest clasts from source, transport, selective deposition	finer	better	positive
IIIB	Erosion capable of removing all clasts, transport, then selective deposition	coarser		
IVA	Current with excess capacity erodes into bed, wanes, selective deposition	fining*	poorer	positive*
IVB	Current with excess capacity erodes into bed, wanes, total deposition			uncertain*

Cases I–III from McLaren (1981); Case IV added.

*Constant changes to mean and skewness with constant incorporation of material and deposition.

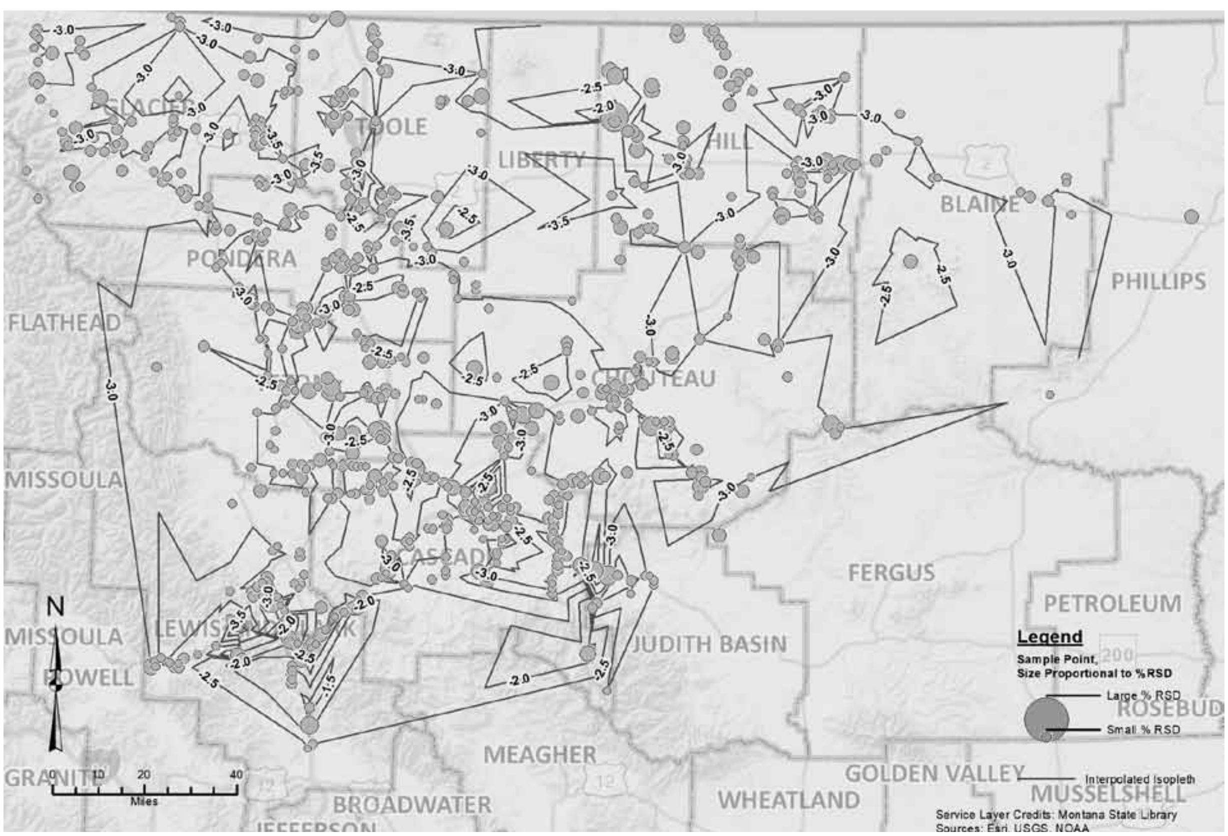
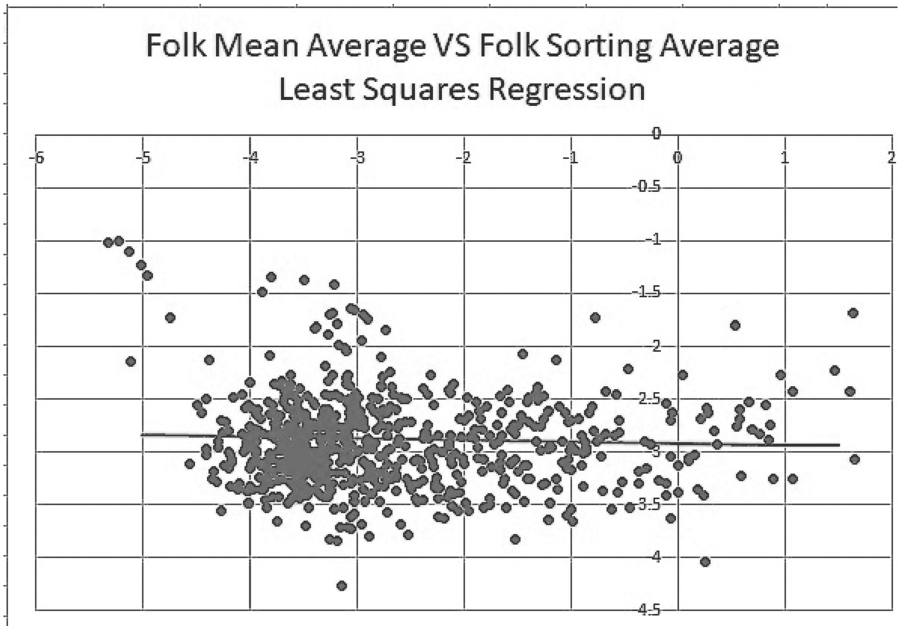


Figure 15. Map of study area showing sorting coefficient per Folk and Ward (1957). The strength of trends or patterns in these data is underwhelming.



N	699		
m =	-0.01643		
B=	-2.91621		
x	y = mx+b		
-5	-2.83407		
1	-2.93264		
0	-2.91621		
1	-2.93264		
1.5	-2.94085		
Byx =	0.886281		
R	-0.05		Correlatiom Coefficient
R^2	0.0022		Coefficient of Determnation

Figure 16. Mean versus sorting using Folk and Ward (1957). The term "average" in the title refers to the fact that each point represents an individual gravel deposit for which a single datum (mean, sorting) was obtained. Sorting is poorly developed and does not appear to vary with mean. A linear regression was applied as shown.

9. Skewness is poorly developed and is not diagnostic.
10. Kurtosis is generally higher away from the mountains and in canyons; however, source materials that could produce higher kurtosis are also present in the area.
11. Scatter plots indicate very noisy data or lack of correlation. More than one scenario for weathering, transport, and deposition could explain this; there is no unique solution.
12. The C-M diagram shows strong correlation with modern river terrace and beach deposits.

Inferences regarding depositional processes and comparison of working hypotheses will be presented in Part II.

Acknowledgements

This project was truly a team effort. Data collection 25 years ago was performed by Beverly Oard and Krista Koljonen with the cooperation of Montana Department of Transportation personnel. The completion of analysis was made possible by a research grant from the Creation Research Society, and TD&H Engineering provided bare-bones hourly rates. Cindy Wojciechowski went beyond requirements entering data with amazing accuracy. James Hiersche donated hours of his time programming the spreadsheet and processing the data. While my coworkers may not be convinced of my position on Earth history, they gladly contributed to the advancement of science through this project. Michael Oard provided an invaluable review of the first draft of this paper and encouragement and assistance over many years. *Deum laudo* (Proverbs 20:15,17).

Glossary

alluvial – deposition by flooding rivers or similar overbank processes

braid plain – a plain formed by anastamosing or braided channels

capacity – the amount of material a stream can transport without reference to size (e.g., large amount of clay or fine sand)

competence – the size of particles that can be moved by a current; adequate current strength (i.e., bed shear stress) to transport larger particles (e.g., gravel)

diluvial – in general (*sensu stricto*), the term refers to the Deluge of Genesis 7–8, though it is sometimes used (*sensu lato*) for processes or deposits associated with any megaflood

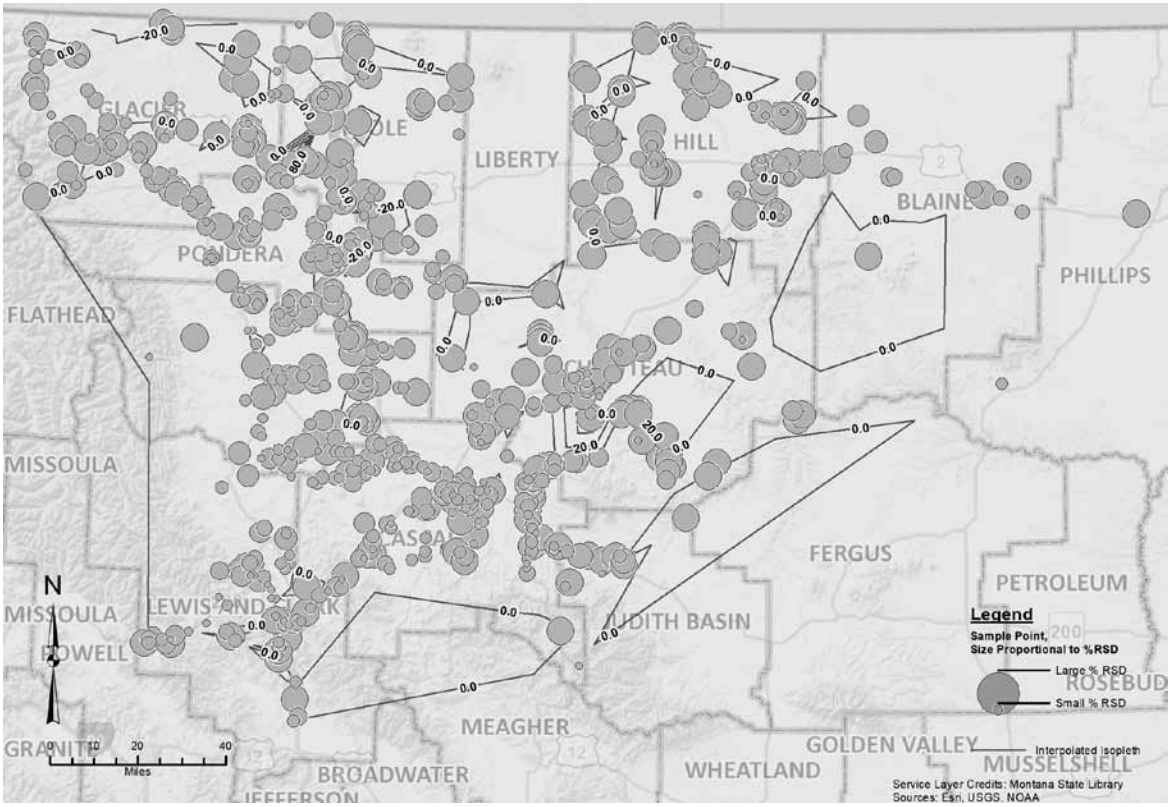
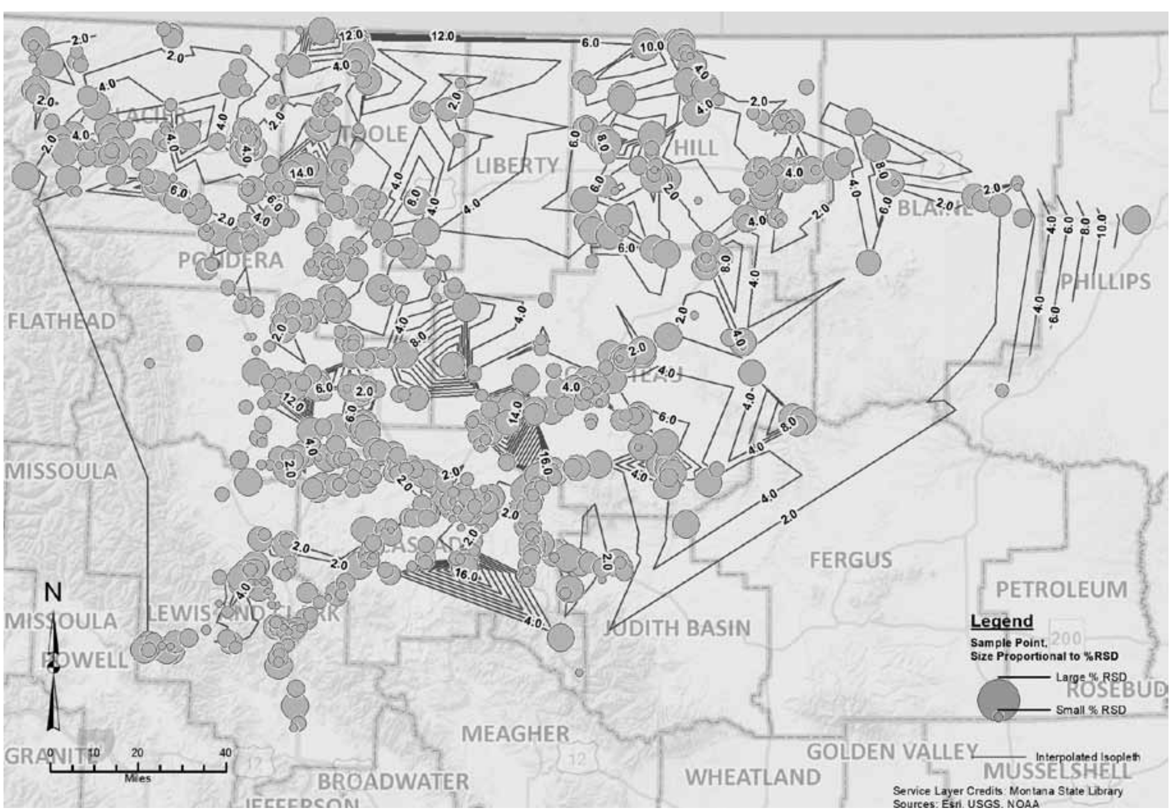
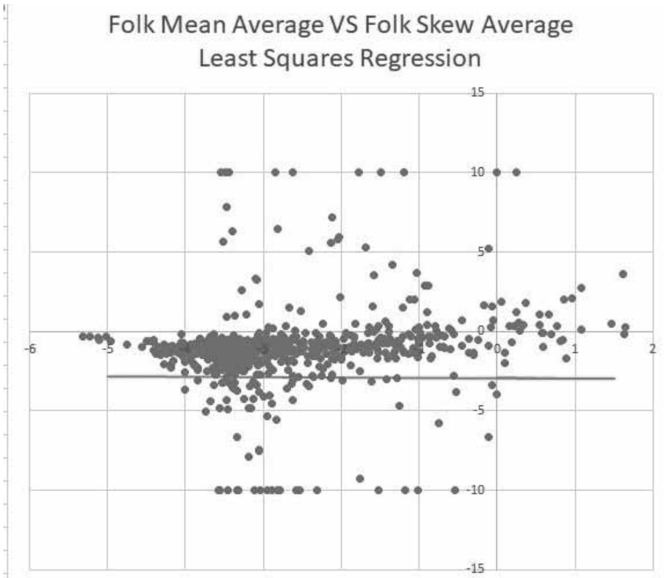


Figure 17 ***(above)*****. Map of study area generated for Folk and Ward skewness results.**

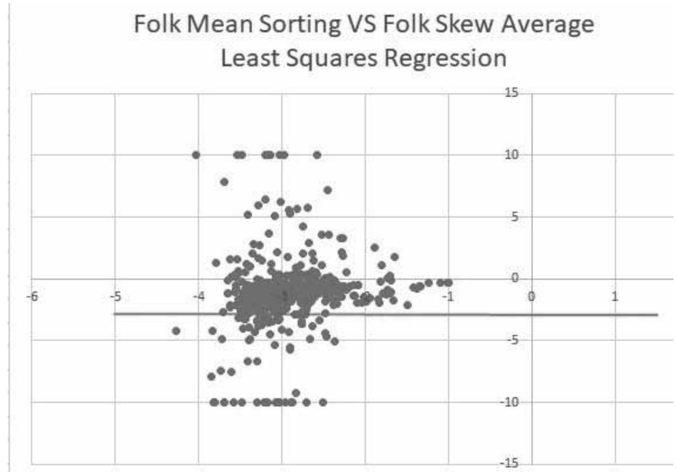
Figure 18 ***(below)*****. Kondolf and Wolman (1993) skewness results.**





N	699	
m =	0.3655	
B=	23.2243	
x	y = mx+b	
-5	21.3969	
1	23.5898	
0	23.2243	
1	23.5898	
1.5	23.7725	
Byx =	0.4116	
R	0.18	Correlation Coefficient
R^2	0.0313	

Figure 19. Mean versus skewness using Folk and Ward (1957). Linear regression applied.



N	699	
m =	0.7980	
B=	-1.1408	
x	y = mx+b	
-5	-3.1922	
1	1.5961	
0	0.7980	
1	1.5961	
1.5	1.9951	
Byx =	0.3999	
R	0.13	Correlation Coefficient
R^2	0.0180	

Figure 21. Spreadsheet output of sorting versus skewness. Typically, an important comparison, in this case it shows no strong trends with a flat linear curve fit. Distant outliers were truncated at ±10 to enhance legibility.

Figure 20 *(left)*. Camrose Colony gravel pit near Ledger, Montana. This area is dominated by glacial material, and a few of the rocks in this pit are exotics believed to have been glacially transported.

fluvial – deposited by streams within their channels

lacustrine – deposition or other processes in a lake

littoral – processes operating along a shoreline

paleohydrology – inferring limitations on past hydrologic processes from existing slopes, deposits, maximum particle sizes, etc.

planation surface – an erosion surface that is noticeably flat and planes rocks without regard to their geologic structure

relative mobility – observation that small particles move more quickly than larger ones in a given current (all else being equal)

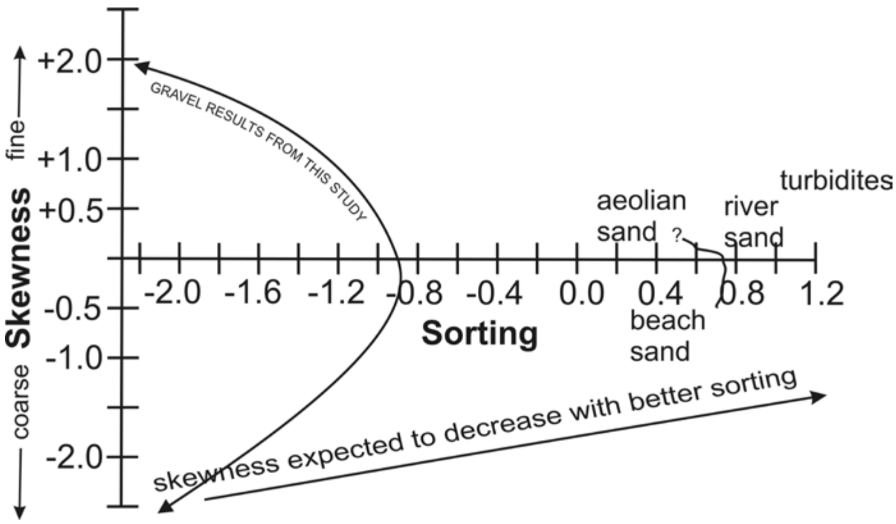


Figure 22. Sorting coefficient versus skewness showing domains of transport processes in sand range and parabola tracing the edge of gravel data from this study (left side of figure). Arrow shows expected decrease in skewness with increase in sorting resulting from action of current during transport.

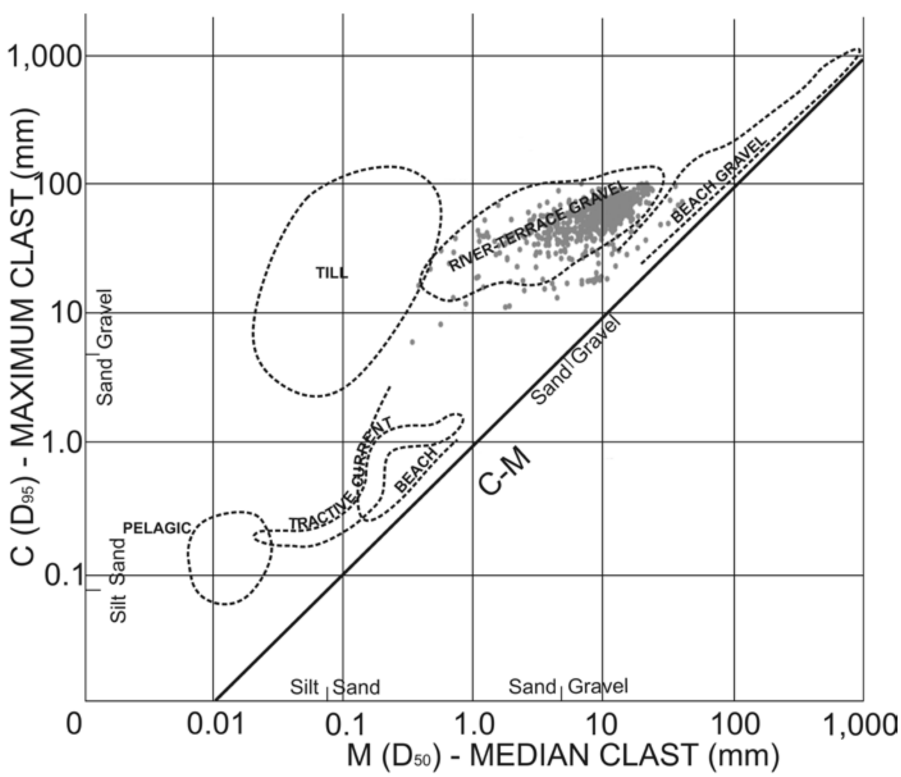


Figure 23. Plot of maximum (C) vs. mean (M) clast size. Maximum is normally defined as D_{99}, but D_{95} substituted here, shifting points very slightly down. Fields corresponding to transport mechanisms are shown by dashed lines as modified from Passega (1964) and Schlee (1973).

winnowing – a special case of relative mobility in which the current is not strong enough to move particles above a certain size or moves them only very slowly while readily removing smaller sizes, leaving a coarser (lag) deposit

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