The Proceedings of the International Conference on Creationism

Volume 4
Print Reference: Pages 361-378

Article 28

1998

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Recommended Citation

Klevberg, Peter and Oard, Michael J. (1998) "Paleohydrology of the Cypress Hills Formation and Flaxville Gravel," *The Proceedings of the International Conference on Creationism*: Vol. 4 , Article 28.
Available at: https://digitalcommons.cedarville.edu/icc_proceedings/vol4/iss1/28

PALEOHYDROLOGY OF THE CYPRESS HILLS FORMATION AND FLAXVILLE GRAVEL

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KEYWORDS

Cypress Hills, Flaxville, paleohydrology, gravel, debris flow, hyperconcentrated flow

ABSTRACT

The Cypress Hills Formation and Flaxville gravel are laterally extensive deposits of gravel and conglomerate. They cap surficial erosion surfaces in southern Alberta and Saskatchewan, Canada, and northern Montana, U.S.A. As detrital sediments, their probable origin is inextricably linked with the question of transport. Most of the clasts are exotic, with the probable source areas in the Rocky Mountains of Montana or Idaho. A variety of potential sediment transport mechanisms is examined and paleohydrologic principles applied to evaluate the probable depositional environment. The probable depositional environment is of great significance in evaluating the diluvial/postdiluvial boundary in the northern Great Plains.

INTRODUCTION

The Cypress Hills are erosional remnants of an extensive, planar, surficial erosion surface located in southeastern Alberta and southwestern Saskatchewan, Canada. The Cypress Hills plateau forms the highest topography between the Rocky Mountains and Labrador [50, p.80]. The Flaxville Plain is a remnant of a similar erosion surface located approximately 100 km south of the Cypress Hills with its western edge approximately 100 m lower than the eastern edge of the Cypress Hills. (See Figure 1 in Oard and Klevberg [40].) The Cypress Hills and Flaxville Plain extend approximately 500 km from west to east. Both erosion surfaces are capped with coarse gravel composed of well-rounded pebbles, cobbles, and boulders. With minor exceptions, the lithologies are exotic [27, 62, 66]. Some of the gravel in the Cypress Hills has been cemented to conglomerate with calcium carbonate. This rock unit averages 40 meters thick and is known as the Cypress Hills Formation [66, p.143]. Interbeds of cross-bedded sand and basal pockets of poorly sorted, unstratified sediments are present in the eastern Cypress Hills Formation and Flaxville gravel. Lime cement is present in some sand interbeds in the Flaxville gravel, forming a weak sandstone. Both the Cypress Hills Formation and Flaxville gravel are underlain primarily by silts, clays and weakly cemented sandstones [49]. Additional background information on general geology, geomorphology, paleontology and stratigraphy of the Cypress Hills and Flaxville Plain can be found elsewhere in this volume [40].

The origin of the Cypress Hills Formation and Flaxville gravel has been a conundrum for uniformitarians for decades. The following features are difficult to explain from a uniformitarian perspective:

- The presence of laterally extensive, planar, surficial erosion surfaces, exceptionally flat, which truncate subjacent strata;
- The presence of laterally extensive sheets of coarse gravel that mantle the erosion surfaces; and,
- Exotic clasts apparently transported 300 to 700 km over slopes of less than 0.1 degrees.

Typical erosion processes produce noticeable relief due to differential weathering, but this is not observed in the Cypress Hills or Flaxville Plain. Could the gravel itself be the resistant caprock? This question is linked to the question of whether a hiatus existed between erosion and deposition, a conventional way of thinking in the field of geology. This may be a hindrance to understanding probable genetic processes. Two clues to the relation between the Cypress Hills and Flaxville erosion surfaces and the superjacent gravel deposits are the nature of the erosion surfaces and the presence of local lithologies throughout the gravels. The erosion surfaces are addressed in Oard and Klevberg [40]. Incorporation of concretions and petrified wood from the subjacent Frenchman/Ravenscrag Formations into the gravel indicates that the gravel that caps these erosion surfaces was itself the corrasive agent. Because the predominant lithologies are exotic, genetic interpretations of the Cypress Hills Formation and Flaxville gravel must be bound to the question of sediment transport. The problem of the origin of these deposits is a problem in paleohydrology.

POSSIBLE SEDIMENT TRANSPORT MECHANISMS

Depositional Characteristics

Both the Cypress Hills and Flaxville gravels are composed of coarse, poorly-sorted gravel consisting of well-rounded pebbles, cobbles, and boulders, principally of lithologies resistant to abrasion, which exhibit abundant percussion marks (Figure 1). The iron oxide patina is also uniform throughout the gravels, yet apparently absent from subjacent strata. Fines are virtually absent from the deposits, yet they predominate in the weakly lithified subjacent sediments. Much of the gravel observed was clast supported with varying degrees of imbrication. Where conglomerate was observed, some of it was matrix supported. Stratification and cross-bedding are evident in sand interbeds which become more abundant in the eastern Cypress Hills [66; 27]. Additional information on the characteristics of the deposits is found in Oard and Klevberg [40].

Sediment Transport Mechanisms

Myriad sediment transport mechanisms have been identified, and work by sedimentologists in recent decades has provided an increasing recognition of the depositional characteristics of many of these processes. It is important to note that very different processes can often produce similar depositional features, and many sediment transport processes grade into one another [18]. Nonetheless, these processes can be categorized in a general way to enhance our understanding of the transport mechanisms and depositional features that result. A summary of sediment transport mechanisms is presented in Table 1.

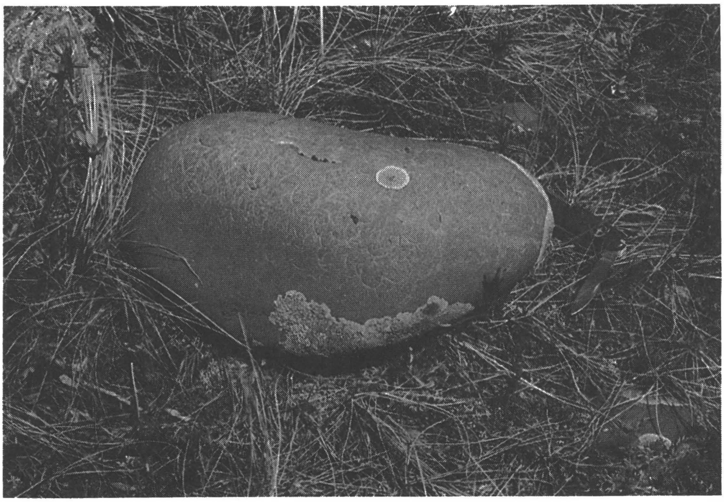

Figure 1 Close-up of quartzite cobble showing percussion marks. Knife blade is 6.4 cm long.

Analysis of Possible Sediment Transport Mechanisms

Coarse sediment transport does not occur with air as the working fluid due to the relatively low density and viscosity of air. The exception is volcanic eruptions, where pyroclastic surges and similar processes can result in rapid deposition of clasts from sand size to boulders. These deposits differ markedly from the Cypress Hills and Flaxville gravels in lithology, texture, lateral extent, and spatial configuration.

Coarse sediment transport by subaqueous mechanisms occurs readily by a variety of processes. Gravel is typically transported by traction currents (e.g. rivers, ocean currents) as bedload. Density currents, in particular turbidity currents, may also transport coarse sediments great distances [39]. Coarse sediments may also be transported as suspended load by very energetic currents [3, 26, 61]. Subaqueous depositional processes appear feasible for the transport of the gravels and are analyzed in greater detail below.

Table 1
SUMMARY OF SEDIMENT TRANSPORT MECHANISMS

FLUID/TRANSPORT MECHANISM	TRANSPORT PROCESS TYPE	DEPOSITIONAL FEATURES	REFERENCES
Air[1]/ Subaerial	Traction[4]	Predominantly high-angle cross-bedded sands (dunes), well-sorted, few large clasts	6, 14, 47, 54, 60
	Density[5]	Pyroclastics; generally volcanic sands, finely stratified to unstratified (Nuées ardentes/lahar deposits)	
	Suspension[6]	Loess (open-structured silt)	
Water[2]/ Subaqueous	Traction	Predominantly low- to high-angle cross-bedded sands (and coarser sediments), including ripples, dunes, plane beds, and antidunes (determined by flow regime); sole markings; vary from poorly to well sorted, clasts angular to well rounded; often erosional base and transitional top	6, 21, 31, 32, 35, 41, 47, 54, 64
	Density	Turbidites; graded sands (may include gravels), silts and clays; flysch; ungraded beds (diamict) and planar stratification; sole markings	
	Suspension	Load-casts (sands); nepheloid clays	
Subaerial Gravity/ Mass Wasting	Slump, toppling failure, wedge failure, rockslide, rock glacier, mudflow, grain flow, debris flow, hyperconcentrated flow, earthflow, creep, solifluction	Generally unstratified, poorly sorted deposits; can range from clay to boulder size; may be clast-supported; may exhibit reverse grading (diamict)	34, 42, 51, 52, 53, 54, 58, 60
Subaqueous Gravity/ Mass Wasting	Submarine landslides	Generally unstratified, poorly sorted deposits; can range from clay to boulder size; slip on one or more planes; usually has hummocky surface (diamict)	17, 54, 60
Ice[3]/ Glacial	Beneath, in or upon ice (till and moraine)	Generally unstratified, poorly-sorted deposits; can range from clay to boulder size (diamict)	22, 23, 24, 54, 59, 60

[1] Subaerial transport and deposition, including steam and volcanic gases.
[2] Subaqueous transport and deposition, including hyperpycnal flows.
[3] Glacial transport and deposition; see subaqueous for glaciofluvial and glaciomarine.
[4] Particles supported by bed but moved along bed by current.
[5] Driving force provided by difference in density between sediment-laden fluid and surrounding fluid.
[6] Particles supported by fluid and transported within the moving mass of fluid.

Subaerial mass wasting mechanisms have been observed to transport coarse sediments. Subaerial mass wasting is expressed in a wide variety of processes, from relatively rigid slumps and toppling failures, to relatively fluid debris flows and mudslides. In nature, some of these processes grade into one another. Although debris flows and hyperconcentrated flows have long been recognized [28, p.386], the importance of these processes has been more widely acknowledged in recent decades due to increased observation and their often devastating impact on urban developments. Debris flow processes have even been invoked to explain some of the surface features observed on Mars [10].

Subaqueous mass wasting generally occurs as submarine landslides. These may resemble subaerial mass wasting processes or transition to turbidity currents. Mass wasting processes, both subaerial and subaqueous, can produce many of the features observed in the Cypress Hills and Flaxville gravels, and are therefore analyzed in greater detail below.

Ice, as a very viscous fluid, is capable of supporting very coarse sediments. Deposition of sediments by glaciers has been observed in historic times. These deposits (till, moraine, etc.) tend to be unstratified; poorly sorted (often rich in fines); with angular, often striated clasts; and with an irregular surface. By contrast, the Cypress Hills (with the exception of the eastern part) and Flaxville Plain are characterized by poorly-sorted, well-rounded gravel, deficient in fines, with stratified interbeds and relatively flat bounding surfaces devoid of glacial topographic features. Geologists generally agree that most of the Cypress Hills and Flaxville Plain were not glaciated [9, 29]. Although catastrophic glacial melting or outburst flooding (jökulhlaup) might be invoked as possible transport processes, they are fluvial in nature and are therefore addressed in the subaqueous process evaluation which follows.

DEPOSITIONAL CHARACTERISTICS OF SEDIMENT TRANSPORT PROCESSES

Sediment transport processes can be very complex, and often more than one process can result in a given depositional characteristic. For example, turbidity currents, debris flows and glacial processes can produce hummocky terrain, outsized clasts in a fine-grained matrix (diamict), striated clasts, and unstratified deposits [6; 31; 32; 36; 39; 54; 55; 64, pp.40,41]. Other criteria would be needed to distinguish these processes. Traction currents can produce plane-bedded sands in both lower and upper flow regimes, though the flow intensities are very different [21, p.139]. Criteria other than the attribute of plane bedding would be necessary to distinguish between lower and upper flow regimes. Matrix or clast support may depend on the relative importance of current winnowing, sediment load, and the effect of fluctuations in intensity on the inequality of threshold bed shear stress for deposition and erosion of fine-grained sediments. In addition to the sediment transport and deposition process, the characteristics of a sediment body also depend on the characteristics of the source sediment. More than one process may act on detrital grains between the time of erosion and deposition. The depositional features summarized in Table 1 are presented as a general guide to typical transport processes and their effects. Each sediment body should be examined carefully in the field to obtain as many data as practicable, recognizing that a certain conclusion as to genetic process is not possible scientifically. Genetic speculation must be guided by the degree of probability according to each possible depositional process.

Possible depositional processes identified above are summarized in Table 2. For comparison, attributes of the Cypress Hills Formation and Flaxville gravel are included. The presentation in Table 2 reflects some of the variety of effects produced by particular processes as well as differences within the Cypress Hills and Flaxville deposits, viz. poorly developed stratification and grading in much of the gravel and matrix support limited to portions of the lithified gravel.

As indicated in Table 2, the best correspondence between typical depositional effects of sediment transport processes and attributes of the Cypress Hills and Flaxville gravels is found with the fluvial/traction current, though turbidity current and fluidized sediment/hyperconcentrated flow processes also show a significant degree of correspondence. The worst correspondence is found with falls/slides. This is expected, as rockfalls, landslides, and similar mass wasting processes are localized, largely mechanical failures. They are included in the table for completeness and as a control against which to evaluate the other processes.

Table 2
DEPOSITIONAL CHARACTERISTICS OF SEDIMENT TRANSPORT PROCESSES

TYPE OF FLOW	ST[1]	GR[2]	SO[3]	IM[4]	CB[5]	RO[6]	PM[7]	CL[8]	MX[9]	DF[10]	REFERENCES
Fluvial/Traction Current	▨	▨ N	▨	▨	▨	▨	▨	▨	◪	▨	2, 6, 13, 21, 54, 64
Turbidity Current	◪	◪ N/R U	◪		▨				▨	▨	8, 16, 17, 18, 19, 31, 32, 35, 37, 43, 46, 55
Mudflow/ Debris Flow		◪ R U						?	▨		12, 13, 19, 20, 43, 46, 58
Fluidized Sediment Flow/ Hyperconcentrated Flow	◪	◪ N/R U				?		▨	▨	▨	5, 12, 13, 19, 20, 42, 43, 46, 58
Grain Flow/ Debris Flow							?	▨	▨		12, 13, 19, 20, 34, 43, 46, 58
Falls/Slides									▨		14
Cypress Hills/ Flaxville Gravels (observed)	◪	◪		▨	▨	▨	▨	▨	◪	▨	27, 66

Shading indicates flow type produces deposits exhibiting given attribute; partial shading indicates flow process sometimes produces given attribute depending on other variables.

[1]Stratification
[2]Grading (**N**ormal, **R**everse, **U**ngraded)
[3]Sorting
[4]Imbrication
[5]Cross-bedding
[6]Rounding of clasts
[7]Percussion marks (speculative)
[8]Clast-supported fabric
[9]Matrix-supported fabric
[10]Downstream fining

Stratification

Where a paucity of sand occurs, the gravel deposits are generally massive, though poorly developed stratification is evident even in the western Cypress Hills (Figure 2; see also Figure 3 in [40]). Stratification develops further with sand interbeds in the eastern Cypress Hills and Flaxville gravel. Stratification is typical of fluvial/traction deposits [6, p.118; 54, pp.172-177]. Turbidities typically produce sharp, erosional bases and stratified (though locally massive) deposits [6, pp.122,123; 54, pp. 178-185]. Debris flows generally lack stratification; though multiple flows could conceivably produce distinct beds [6, p.161], this has not observed [34]. Hyperconcentrated flows (if defined as quasi-Newtonian) can produce weak stratification [58].

Grading

Grading is poorly developed in the Cypress Hills Formation, especially in the western part, but becomes more evident to the east [27]. Compound normal grading was observed by the authors at the Conglomerate Cliffs in the central Cypress Hills (see Figure 3 in [40]). Normal grading is typical of traction deposits, though reverse grading and massive deposits are also observed [54, p.177]. Normal grading is also typical of turbidites [6, p.122], though reverse grading occurs in beds interpreted as proximal turbidites [31]. This is not true of debris flows, as stated by

Figure 2 Horseshoe Canyon, an amphitheater on the northwest flank of the Cypress Hills. Slope exposes ca. 30 m of coarse gravel and carbonate-cemented conglomerate.

Pierson & Scott [42, p.1511]: "In Newtonian mixtures, and in non-Newtonian mixtures with very low shear strength, any sand and gravel particles present are free to settle out of suspension, although fall velocities will be decreased . . . . Such mixtures can be termed nonhomogeneous . . . because the fluid and granular phases are free to act independently (at least partially) of each other while flowing. Suspensions in the volume concentration range of 20-60% . . ., termed 'hyperconcentrated' . . ., generally show this behavior." Grain flow or debris flow deposits are typically ungraded [6, p.163].

Sorting

Well-sorted sediments imply hydraulic action (fluvial/traction current transport process), though lack of sorting does not disprove a fluvial/traction process. "The correlation is best documented for the fine to coarse sand sizes, with sorting improving (decrease of standard deviation) toward the finer sand sizes . . . . Sediments coarser than this are moved by currents that also carry and deposit some finer materials" [6, pp.104,106]. Poorly sorted materials typify turbidites [54, p.173]. Diamicts, sediments composed of large clasts in a fine-grained matrix, are formed both subaerially and subaqueously by mudflows and debris flows [6, p.161; 21, p.188; 54, p.174]. Sorting is unlikely to develop in the laminar flow within a debris flow [6, p.161].

Imbrication

Imbrication implies deposition by a fluvial/traction current process. "Imbrication is well developed, by pebbles of appropriate shape, in tractional deposits that are sufficiently well sorted to permit the particles to come into contact with each other, i.e. in deposits where the larger, platy pebbles are not separated from each other by a 'matrix' of smaller particles" [6, p.108]. Where clasts have been transported in suspension by turbidity currents or debris flow processes, imbrication would not be expected. However, imbrication could occur in turbidites if bedload transport of larger clasts occurred after they dropped out of suspension. Although imbrication is not typical of debris flow or hyperconcentrated flow, a rough alignment of a-axes parallel with the flow direction (roughly 90° from imbrication) was observed in a hyperconcentrated flow on Mount St. Helens, Washington, U.S.A. [58].

Cross-Bedding

Cross-bedding is pervasive in traction deposits and turbidites [6, pp.117-132], though it is replaced by planar bedding at the transition to upper flow regime and at very low current speeds [21, pp.138-146; 54, pp.174-185]. It is not observed in hyperconcentrated flows or debris flows [6, p.161; 21, p.188; 58].

Rounding

Several weathering processes contribute rounding of clasts, one of the most important being abrasion in fluvial transport [6, pp.68-70]. Presumably, abrasion and rounding would also occur in turbidity currents. Rounded clasts have been observed in deposits formed from hyperconcentrated flows [42]. However, rounding is not diagnostic of hyperconcentrated flows. "Roundness data show that at least 69 percent of the -3 to -5 ϕ (8-32 mm) size range in the main body of the first lahar of Pine Creek age originated as eroded stream alluvium. A similarly high degree of rounding is present in the 'ball-bearing bed', but some of this rounding reflects grinding action during lahar transport"[51, p. 39]. Fluid debris flows are also typified by flow not conducive to clast rounding. Hampton states, "A rigid plug of some thickness always exists in a debris flow" [18, p.842]. Clast rounding may therefore result from abrasion in transport or weathering processes preceding transport; however, it is generally indicative of turbulent fluid transport.

Percussion Marks

Intuitively, percussion marks indicate very violent collisions between clasts. Approximately half of the cobbles observed in the Cypress Hills Formation and Flaxville gravel display percussion marks. A paucity of research on this topic prevents a detailed analysis of percussion marks, but they evidently imply turbulent transport. Turbulent transport is expected from a fluvial/traction process or the basal portion of a turbidity current. It is unlikely with a fluidized mass wasting (debris flow) process: "Thus it appears that the Reynolds number is quite low (of the order of 10 to 100) so that it is probable that the flow is indeed laminar in nature"[6, p.161]. An exception may be hyperconcentrated or grain flows in which dispersive pressure (particle interaction) is the principal clast support mechanism.

Clast-Supported Fabric

Clast-supported fabric may be generated by a variety of processes. In fluvial/traction current transport, clast support may be indicative of current competence or winnowing effects. Dense turbidity currents may produce clast-supported gravel or conglomerate, often reversely graded [31]. Scott et al [53, p.5] state: "Both cohesive and noncohesive debris flows can leave behind clast-supported whaleback bars at sites of rapid energy loss." Speaking of hyperconcentrated flows, they continue [53, p. 9]: "The most obvious feature that differentiates these deposits from debris flow deposits is their undispersed, entirely clast-supported texture." Clast-supported texture may occur in all of these transport processes when the source area is well-sorted sediment.

Matrix-Supported Fabric

Matrix support is not typical of traction deposits [54, p.104], though matrix may be deposited with coarse sediments, resulting in poorly sorted deposits [6, pp.104,106]. Matrix support may also reflect sediment supply. Matrix support is typical of certain facies in turbidites [6, 31, 32, 35, 46, 54]. It is also typical of thick debris flows, but not hyperconcentrated flows, as observed by Pierson & Scott [42, p.1513]: "An increase of 3-4% [of water] by weight can dilute the slurry to the point where it cannot hold gravel-size particles in suspension. The lahar clearly flowed easily, and the unsorted, nonstratified deposits indicate that gravel was held in suspension."

Matrix support of three types is observed in the subject deposits. Lime-cemented conglomerate of the Cypress Hills Formation is locally matrix-supported but appears fluvial in origin [40]. Deposits capping ridges east of Glacier National Park, U.S.A., (see Figure 1 in [40]), equated with the Flaxville surface by Alden [1] resemble debris flow deposits. Leckie and Cheel [27, p.1924] interpret the matrix-supported basal deposits of the eastern Cypress Hills Formation as debris flows based on lack of stratification, outsized clasts, and "disorganized" fabric, as well as fossil content. They interpret these as bank collapse deposits, noting the lack of conditions, such as steep slopes (high initial potential energy), generally required for debris flow genesis, and the localized lateral extent of the deposits. If they truly mean *disorganized* rather than *unorganized*, then vestiges of the organization (stratification) must be present. Since they assert that these basal deposits are intimately associated with turbulent deposits, the latter may be the case, implying fluvial genesis of the basal deposits. Lack of fossil content in the coarse, "turbulent" superjacent sediments may have resulted from highly energetic, abrasive sediment transport conditions.

Downstream Fining

Downstream fining is typical of traction currents [2; 54, p.174] and turbidity currents [32]. It is not typically observed in viscous debris flows, where most of the sediment is transported as a relatively rigid plug [18, p.842]. More fluid debris flows may produce complex spatial particle size distributions: "Previous sections point to two key phenomena that characterize unsteady, nonuniform debris flow motion: (1) Fluid pressures greater than hydrostatic pressures exist in debris flows and can enhance flow efficiency, but cannot exist during steady, uniform motion. (2) Debris flows move as a surge or series of surges, in which coarse-grained heads that lack high fluid pressure restrict the downslope motion of finer-grained debris that may be nearly liquified by high fluid pressure . . . . A coherent theory that predicts the coupled evolution of these phenomena is currently unavailable"[Iverson, p.277]. Pierson & Scott [42, p.1513] concur: "Dense, non-Newtonian slurries flowing in open channels may exhibit characteristics that are quite different from normal streamflow: (1) a steep, lobate snout at the flow front, commonly containing a high concentration of boulders; (2) lateral levees composed of the coarsest particles available; (3) a tendency to flow in pulses or surges; (4) a tendency for the coarsest particles in the mixture to be segregated toward the surface and the center of the flow; and (5) a tendency for shear to be concentrated at flow boundaries and for rigid plugs to form toward the center of the flow."

ENERGY CONSTRAINTS

An additional means of evaluating the probability of possible genetic processes is an energy analysis. The minimum work required to transport the minimum volume of observed sediment the minimum distance must be less than minimum initial available energy. The work done on the system is equal to the product of the resisting force (or stress on a unit width basis) and transport distance. Initial energy may be provided by a combination of potential and kinetic energy. Potential energy would have been available to all transport processes following creation of the Cypress Hills and Flaxville erosion surfaces. Additional potential energy may have been available if the source areas for the sediments were significantly higher than these erosion surfaces. Kinetic energy may have been available from currents (hydraulic process) or explosions (volcanic processes), though evidence of the latter is not observed in the Cypress Hills or Flaxville Plain.

Table 3 summarizes physical characteristics of the sediment transport processes addressed above relative to characteristics of deposits. The stress terms listed in Table 3 represent fluid shear and are not directly comparable to bed shear stress when the velocity profile is not known. They are, however, representative of the fluid behavior. Gradations between the fluid types/grain support mechanisms do occur in nature, though the transitions may be abrupt [42, p.1512].

Table 3

PHYSICS OF SEDIMENT TRANSPORT PROCESSES

TYPE OF FLOW	CLAST SUPPORT MECHANISM	TYPE OF FLUID	STRESS TERM	REFERENCES
Fluvial/Traction Current	Streambed	Newtonian	$\tau = \mu \cdot du/dy$ (laminar) $\tau = \mu \cdot (du/dy)^2$ (turbulent)	4, 6, 21
Turbidity Current	Turbulence	Newtonian	Similar to fluvial/traction but with two interfaces	6, 18
Mudflow/ Debris Flow	Matrix Strength	Bingham Plastic	$\tau = \tau_y + \mu_m \cdot du/dy$	6, 18, 21
Fluidized Sediment Flow/ Hyperconcentrated Flow	Pore Fluid Expulsion	Pseudoplastic	$\tau = \tau_y + \mu_m \cdot du/dy + \zeta(du/dy)^2$	6, 18, 21
Grain Flow/ Debris Flow	Dispersive Pressure	Pseudoplastic	$\tau = \tau_y + \mu_m \cdot du/dy + \zeta(du/dy)^2$	4, 6, 21
Falls/Slides	Failure Surface	Solid/Discrete Block	Various	60, 63

τ = fluid shear stress
μ = kinematic viscosity
du/dy = vertical velocity gradient
τ_y = yield strength
μ_m = viscosity of mixture
ζ = turbulent-dispersive parameter

Newtonian Fluids

Rivers flow under the impetus of gravity alone. Flow is determined by available water, bed slope, and energy dissipative factors (e.g. bed shear stress). Currents in lakes and oceans are dependent on wind and thermal gradients. At relatively low sediment concentrations, these current systems behave as Newtonian fluids. As shown in Table 3, shear stress is directly proportional to the fluid viscosity and the velocity gradient (laminar flow) or square of the velocity gradient (turbulent flow). Turbidity currents are driven by density differences and loss of gravitational potential energy. Unlike fluvial systems, turbidity currents have resisting shear forces on both the bottom and top of the flow.

Non-Newtonian Fluids

As described by Iverson [20, p.247], subaerial mass flow processes are more complex than Newtonian processes: ". . . debris flow motion involves a cascade of energy that begins with incipient slope movement and ends with deposition. As a debris flow moves downslope, its energy degrades to higher entropy states . . . ." Newtonian or non-Newtonian behavior is very dependent on sediment mineralogy. "Sediment-water mixtures that have negligible amounts of silt and clay dispersed in the fluid phase appear to maintain Newtonian behavior up to very high concentrations: as great as 50% by volume for mixtures containing coarse particles of relatively uniform size . . . or as great as 35% by volume for more poorly sorted sediment . . . . With increasing amounts of silt and/or clay, sediment-water mixtures may acquire a yield strength. Mixtures that contain predominantly silt acquire a yield strength in the range of 30-35% volume concentration . . . . Clay-rich mixtures may exhibit yield strength at volume concentrations as low as 10% or less . . ."[42, p.1511].

Non-Newtonian fluids may be modeled as Bingham plastics or pseudoplastics. To compare flow resistance of a Bingham plastic to a Newtonian fluid, evaluation of both the yield strength (negligible for Newtonian fluids) and viscosity is necessary. "Fluid bulk densities of debris-flow slurries typically range from about 1.8 to 2.3 g/cm^3 . . . or roughly 50 to 75% sediment by volume, depending on grain-size distribution. Such mixtures are on the order of 10^4 to 10^5 times more viscous than water, and they characteristically possess a finite yield strength . . . . The yield strength must be overcome by applied stress before deformation (flow) is possible"[45, p.285]. The driving force must therefore be of greater magnitude for a Bingham plastic than a Newtonian fluid. This is observed in practice, where debris flows are not normally observed on slopes of less than 5° [6, p.161], whereas Newtonian fluids (e.g. rivers) flow on very slight slopes. The importance of an adequate driving force is stressed by Hampton [18, p.843]: "If a debris flow is to remain in motion, internal resistance must be continuously overcome by the downslope pull of gravity, irrespective of whether the matrix is strong enough to support all of the grains."

A rigid plug normally forms in the center of a debris flow, restricting shear to the interface between the plug and the surrounding sediments [18, p.842]. The resulting motion can be a combination of grain interaction ("grain temperature" or "dispersive pressure"), matrix yield strength, and fluid expulsion, with a complex, surging behavior [6, p.159-163; 20; 34; 54, p.193-195]. "The Bingham plastic model is well suited to homogeneous suspensions of fine particles, particularly at low rates of deformation. The analysis of coarse sediment mixtures is somewhat more complex and involves an additional shear stress due to particle impact. The dispersive shear stress is shown to increase with three parameters: the second power of the particle size, the volumetric sediment concentration, and the second power of the rate of deformation. It is important to recognize that the dispersive stress is proportional to the product of these three parameters; therefore, high values of all parameters are required to induce a significant dispersive shear stress"[21, p.189]. Debris flows are often supported by suddenly mobilized pore fluid pressures; the flows persist until the pore fluid escapes [6, p.159,160]. Although a reduction in flow resistance has been postulated with high sediment concentrations in hyperconcentrated flows, this has not been supported by field data [42, p.1522].

Although the physics (and even the terminology) of debris flows, mudflows, and hyperconcentrated flows is not well worked out, analogues exist that permit a rough estimate of energy constraints. Iverson [20, p.249] tabulates the ratio of runout distance to elevation loss (L/H) for several mudflows and debris flows. The L/H values observed range from 2 to 25, the largest value being for the Osceola mudflow in Washington, U.S.A. Iverson [20, p.248] notes a roughly logarithmic relationship between L/H and volume. Extrapolating from the approximately 10^9 m^3 of the Osceola mudflow to 10^{11} m^3 for the Cypress Hills Formation, a liberal estimate for L/H would be 30. On this basis, the initial elevation of the center of mass necessary to produce the Cypress Hills Formation as a fluidized sediment flow would be 10 000 m for the proximate end of the Cypress Hills (300 km distance) and 24 000 m for the distal end of the Flaxville Plain (700 km).

The work of Iverson [20, p.248] indicates that even these estimates are far too liberal for sediment resembling the gravels of the Cypress Hills and Flaxville Plain: "When the sand-gravel mix is replaced by well-sorted gravel, however, the influence of water on the outcome of experiments changes: dry gravel produces L/H>2, but water-saturated gravel produces L/H<2. Thus water enhances the mobility of poorly sorted debris flow sediments in a manner not manifested by mixtures of well-sorted gravel and water, and experiments with water-gravel mixtures provide a poor surrogate for experiments with realistic debris-flow materials." This may indicate that the viscous resistance of the water (providing negligible pore pressure) more than compensates for any reduction it affords in grain surface friction. Runout distance is greater for fine-grained mudflows [70], reaching up to 120 km in the Cascade and Andes Mountains [20, p.249; 44]. Debris flows require significant initial potential energy (i.e. steep slopes), tend to be localized, and are generally depositional rather than erosional [6, 45, 70].

Falls/Slides

Mechanical failures, e.g. slumps, rockslides, and toppling failures, tend to be highly localized and relatively immobile. These relatively rigid mass wasting mechanisms are incapable of movement on slopes as low as those observed in the study area.

FLUID MECHANICS OF HYPERCONCENTRATED FLOWS

Most hyperconcentrated flows have been studied in mountainous regions, since they are typically confined to steep mountain drainages [6, p.163; 12; 20; 45; 65; 70]. However, hyperconcentrated flows were inferred by Lord and Kehew [30] for formation of the Souris, Des Lacs and Moose Mountain spillways through catastrophic drainage of glacial lakes. By dividing the estimated volume of sediment eroded by the estimated volume of glacial Lake Regina, they estimated 20% sediment by volume [30, p.672]. Because the estimated depths appeared excessive, they concluded that use of the DuBoys-Limerinos-Shields-Manning method produced erroneous results, and that the flow was actually hyperconcentrated. They correctly noted that the abundance of montmorillonite (a water-sensitive clay of the smectite group) in the sediments in which the channels are incised could produce a significant yield strength in the fluid [30, p.672]. Although they propose a hyperconcentrated flow, Lord and Kehew acknowledge that deposits in the center of the channel are indicative of Newtonian flow [25; 30, p.671]. By estimating flow depth from the channels and accommodating the effect of a mobile bed on the value of *n*, they were able to reconcile these differences using the Manning equation, obtaining values in agreement with an empirical relationship for jökulhlaups [30, p.671], though channel dimensions were difficult to estimate [25].

Lord and Kehew [30, p.671] recognize a significant disparity between the critical shear stress (τ_c) values of Shields and those of methods derived for coarse sediments. This disparity arises partly from the differences caused by streambed armoring and shielding, which were probably minor in the Souris, Des Lacs and Moose Mountain spillways [30, p.672]. A more serious problem arises from extrapolation of Shield's equation for sand entrainment in 1 m flows to coarse sediments and deep flows. If buoyancy effects are important, τ_c is reduced even further.

Neglect of the change in density for heavily sediment laden flows can also lead to significant errors. If the flow transported 20% sediment by volume, the estimated flow depth is reduced by 25%. If τ_c = 58

Pa, the resulting flow depth would be 24 m; for τ_c = 115 Pa, flow depth would be 47 m. These flow depths are even less than Lord and Kehew estimated from geomorphology. However, viscosity also increases with sediment load, and increased viscosity would require increased depth to maintain flow. Using the methods of O'Brien and Julien [21, p.190], the viscosity of the postulated Souris fluid may have been 8 to 10 times the viscosity of clear water. Although still Newtonian on both theoretical [21, p.190] and sedimentological grounds [30, p.671], the resulting fluid would begin to exhibit yield strength. Such a fluid would be called "hyperconcentrated" according to some [42] but not others [6].

For hyperconcentrated flows, Julien [21, p.191] provides the following relationships between sediment loads and yield strength and dynamic viscosity, respectively:

$$\tau_y \approx 0.1e^{3(Cv-0.05)} \tag{1}$$

where $C_v > 0.05$
C_v = volume fraction sediment
τ_y = yield strength (in Pa)

$$\mu_m \approx \mu \bullet (1 + 2.5C_v + e^{10(Cv-0.05)}) \tag{2}$$

where $C_v > 0.05$
μ = kinematic viscosity of clear water
μ_m = kinematic viscosity of mixture

The above equations describe water-sediment mixtures in which the sediment is predominantly sand. Since silt and clay are not observed in the Cypress Hills Formation and Flaxville gravel, these equations are most appropriate. "Simplifications of the quadratic rheological model are possible under the following conditions: (1) The Bingham model is applicable when $\Pi_\tau \rightarrow 1$ [dimensionless excess shear stress term]; moreover, the fluid is Newtonian when $\tau_y \ll \tau$" [21, p.193]. The effects of high sediment loads on fluid mixture properties can be inferred from the values in Table 4, in which τ_c (critical stress for bedload movement, adjusted for buoyancy) is substituted for τ (bed shear stress).

Table 4
EFFECTS OF SEDIMENT CONCENTRATION ON FLUID PROPERTIES

C_v (%) [1]	$\mu_m \bullet 10^3$ (N•s/m^2) [2]	ρ (kg/m^3) [3]	$\mu/\rho \bullet 10^6$ [4]	τ_y (Pa) [5]	τ_c (Pa) [6]
0	1.31	1000	1.31	0.00	115
5	2.78	1085	2.56	0.10	69
10	3.79	1170	3.24	0.12	65
15	5.35	1255	4.26	0.14	62
20	7.80	1340	5.82	0.16	58
25	11.7	1425	8.21	0.18	54
30	18.1	1510	12.0	0.21	51
35	28.4	1595	17.8	0.24	47

[1] Volume percentage sediment (sand)
[2] Dynamic viscosity of mixture x 10^3
[3] Mixture density
[4] Kinematic viscosity (v) x 10^6
[5] Yield strength of mixture
[6] Critical shear stress based on clast size in clear water, reduced to compensate for buoyancy effects

Several characteristics of the fluid mixture described in Table 4 are evident:

- Viscosity increases with increasing sediment load. This acts to increase the force resisting flow of the fluid.

- Density increases with increasing sediment load. This acts to increase the driving force on the fluid.

- Viscosity increases more rapidly than density, resulting in a net increase in resistance to flow.

- A yield strength is evident at sediment concentrations as low as 5%.

- Yield strength is much smaller than shear stress, indicating the fluid behavior is Newtonian.

Because sediment effects can be complex and partially compensate for each other, they are generally neglected in general engineering practice unless sediment concentrations are particularly high and fluid behavior becomes significantly non-Newtonian. Hyperconcentrated flows approximate Newtonian flows

[12, p. 288; 13, p.116], and the transition to non-Newtonian flow is relatively abrupt [12, p.289-291]. Flows with yield strengths of less than about 10 to 40 Pa are approximately Newtonian, even with sediment volume concentrations as high as 50% [13, pp.114,116]. Based on the characteristics of the deposits in the study area, energy constraints, and the properties of hyperconcentrated flows, the paleohydrology of the Cypress Hills Formation and Flaxville gravel is best modeled as Newtonian flow.

PALEOHYDROLOGICAL ANALYSIS

Sediment transport capabilities of a current system may be evaluated in terms of *competence*, the maximum particle size or weight the current is capable of moving, and *capacity*, the maximum amount of bed load a current can transport. Minimum values of stream competence can be inferred from observed clast dimensions. Paleohydraulic estimation of capacity is not as tractable. Typical engineering equations for open channel flow are often difficult to apply to paleohydraulic reconstructions, since data available to the engineer (e.g. design depth and width) are not available to the geologist seeking to apply field data to the study of earth history. Various laboratory and field studies have provided data enabling correlation of competence with current speed, flow depth, and other hydraulic variables. Definite values for discharge, velocity, and other paleohydraulic parameters cannot be provided without historic data; geologic data provide only constraints by analogy to observed fluvial processes. Therefore, these methods enable calculation of minima based on competence; actual flows may have been substantially greater, especially if governed by capacity.

Several similar equations (e.g. Chezy, Manning) are in common use for the design of open channels. These and computational analogues may be reviewed by the interested reader in introductory texts to fluid mechanics or open channel flow. In general, these equations describe relationships in steady, uniform flow. Flash floods are examples of unsteady flow, flow in which the velocity and discharge change with time. Most river channels are examples of nonuniform flow, in which depth, width, and cross-sectional area vary with distance. Nonetheless, equations developed for engineered channels have been applied to unsteady flow [12] and nonuniform flow [56] in modern (historic) settings with minimal error. Myriad empirical relationships have been established between particle size and hydraulic parameters, many of which have been summarized by Maizels [33]. Church, Wolcott and Maizels [11] provided corrections to Maizels' article and showed the basic equivalence of the various methods, based in part on the observation that the ratio d_{84}/d_{50} (d_n = opening size passing *n*% of particles in the mixture) for most modern fluvial deposits is approximately 2:1. They recommended use of the Keulegan Equation. Like most open channel flow equations, the Keulegan Equation requires knowledge of flow depth.

Various methods for estimating τ_c from particle size have been developed [69]. Considerable variation exists due to other stream variables; however, the methods of Costa [12], G. Williams [68] and Baker and Ritter [69] appear consistent with field data for coarse sediment transport and most applicable to the Cypress Hills and Flaxville sediments. These methods were employed to obtain various values of minimum current speed and bed shear stress for the study area. Particle sizes used in the calculations below were intermediate diameters from the largest in situ clasts of unequivocal fluvial origin observed by the authors.

Table 5
BASIS FOR SHEET FLOW INTERPRETATION OF GRAVEL DEPOSITS

EVIDENCE AGAINST CHANNEL OR BAJADA DEPOSITION	EVIDENCE FOR SHEET DEPOSITION
Lack of small, discontinuous stream terraces	Vast, gravel-capped erosion surfaces
Lack of cut-and-fill or channel structures	Laterally extensive, continuous sheet or veneer of gravel
Lack of rapid lateral facies changes	Continuous gravel sheet showing slight development of laterally continuous stratification
Lack of interfingering or fan-shaped deposits characteristic of alluvial fan and bajada	Continuous gravel conformable with erosion surface

Based on the nature of the observed gravel deposits, sheet flow (width>>depth) is assumed (see Table 5). This approximates uniform flow. For steady flow, the head loss must equal the loss in potential energy along the flow path. Peak flow approximates steady, uniform flow and is of chief interest to this study since it coincides with maximum stream competence. Using the momentum equation for incompressible flow, and recognizing that steady flow implies a balance between the resisting bed shear stress τ and driving gravitational force, the net unit force parallel to the bed can be expressed as:

$$h\gamma\sin\theta = \tau \tag{3}$$

h = depth of flow
γ = unit weight
θ = slope angle

The minimum shear stress is determined from the maximum particle size using an arithmetic mean of the methods of Costa and Baker and Ritter as modifed by Williams. The flow depth is determined from a free-body diagram equating the component of the weight parallel to the slope with the bed shear force. Having solved Equation (3) for h, the friction factor can be calculated from the Keulegan Equation [11, p.476]:

$$f = [2.03 \cdot \log(12.2h/d)]^{-2} \qquad (4)$$

f = the friction factor
h = flow depth
d = particle diameter (b-axis larges clast)

The Keulegan Equation is not sensitive to the choice of particle size. Values such as d_{50}, d_{60}, or d_{84} might be more appropriate in most cases. However, the assumption of Church, Wolcott and Maizels that d_{84}/d_{50} = 2:1 is not applicable to the Flaxville gravels. Calculations by one of us from grain-size distribution data from several gravel pits in the Turner, Montana, area show d_{84}/d_{50} values averaging 3:1, indicating the distributions are skewed to the coarser particles.

For most flow conditions, suspended sediment effects are insignificant [11, p. 477] (see Table 4), and they are therefore neglected in these calculations. By L'Hôpital's Rule, the value of the hydraulic radius approaches the flow depth as the channel width increases. Substituting the flow depth for the hydraulic radius, and using the friction factor obtained from the Keulegan Equation, the magnitude of the mean velocity is calculated from the Chezy Equation:

$$V = \sqrt{(8ghS/f)} \qquad (5)$$

V = mean current speed
g = acceleration due to gravity
S = slope (small angle approximation)

Having obtained flow depth and mean current speed, unit discharge can be estimated. The Froude Number is calculated from V and g; a Froude Number of unity indicates critical flow, at which specific energy is a minimum and flow unstable. A Froude Number less than one indicates subcritical flow. Values for independent variables and results of calculations are summarized in Table 6 below.

Table 6
PALEOHYDRAULIC COMPETENCE ESTIMATES
Transport as Bed Load

LOCATION[1]	d (mm)[2]	τ_{min} (N/m^2)[3]	h_{min} (m)[4]	Slope	V_{min} (m/s)[5]	q (m^3/s)[6]	Fr[7]	Re[8]
Flat Top Mtn. - Cypress Hills	240	122	3.2	0.00385	4.4	14	0.79	$4.38 \cdot 10^7$
Cypress Hills	229	115	7.7	0.001515	5.1	39	0.58	$1.20 \cdot 10^8$
Cypress Hills (sinuosity = 2)	229	115	15.5	0.00076	5.7	88	0.46	$2.67 \cdot 10^8$
Turner	229	115	11.2	0.001051	5.4	60	0.52	$1.84 \cdot 10^8$
Opheim	210	100	6.5	0.001578	4.7	30	0.59	$9.23 \cdot 10^7$
Flaxville	190	91	13.3	0.0007	5.1	67	0.45	$2.05 \cdot 10^8$
Flaxville (sinuosity = 2)	190	91	26.5	0.00035	5.6	148	0.35	$4.53 \cdot 10^8$
Flaxville (sinuosity = 3)	190	91	39.8	0.00023	5.9	235	0.30	$7.17 \cdot 10^8$

[1] Sinuosity at indicated location assumed to be unity unless otherwise indicated
[2] Dimension of intermediate diameter of largest particle in millimeters
[3] Minimum shear stress in Newtons per square meter based on maximum particle size
[4] Minimum depth in meters to produce steady flow at minimum shear stress
[5] Minimum mean current speed in meters per second calculated using Keulegan and Chezy Equations
[6] Discharge in cubic meters per second per meter width
[7] Froude Number: $Fr > 1$ = supercritical flow; $Fr < 1$ = subcritical flow
[8] Reynolds Number: $Re < 2 \cdot 10^3$ = laminar flow; $Re > 10^4$ = turbulent flow

The above calculations assume transport of gravel as bed load. Ubiquitous percussion marks indicate that at least part of the transport was via intermittent suspension. The percussion marks cover well-rounded cobbles of hard quartzite, indicating some distance of transport before the observed percussion marks formed. That these percussion marks are also evident in samples from the Flaxville Plain indicates significant chemical or physical weathering did not take place before the rocks were deposited in their present locations.

The minimum mean current speed (V_{min}) for suspended load transport can be estimated from the settling velocity of suspended particles (V_t) based on the observation that the ratio of V_{min}/V_t is at least 12 [6, p. 100]. Assuming equant quartzite particles (for simplicity), the terminal velocity of the particles can be balanced with the drag force resulting from current turbulence. This results in the following expression:

$$V_{min} \geq 12.5\sqrt{(2F_D/(C_D A \rho))} \tag{6}$$

V_{min} = minimum average speed of the current
F_D = drag force
C_D = drag coefficient relative to turbulence (i.e. counteracting gravity)
A = particle area normal to the gravitational gradient
ρ = fluid density

The drag coefficient is determined from a figure for axisymmetric bodies [48, p. 425]. For 100 mm cobbles, this equates to a minimum mean current speed of 14 m/s. In the observed deposits, equant particles are uncommon, and most are oblate or bladed. For bladed particles, the estimates become less precise due to changes in *A* and C_D with rotation in the current. Assuming that larger rocks inherited percussion marks from impacts by smaller cobbles, a conservative estimate for maximum particle size in suspension would be 150 mm. A reasonable estimate for transport of the 150 mm (b-axis) bladed cobble in suspension is a V_{min} in excess of 30 m/s. Evidence indicating that rocks as large as 150 mm have been transported in suspension has been documented from a gravel-capped erosional surface below the Flaxville surface elevation near Great Falls, Montana, approximately 100 km from the probable source area [26]. If the percussion marks were formed during transport from the vicinity of Flat Top Mountain to the Cypress Hills, the most potentially energetic study reach, the resultant unit discharge may have been in excess of 200 m^3/s per unit width, as shown in Table 7.

Table 7
PALEOHYDRAULIC COMPETENCE ESTIMATES
Transport as Suspended Load

LOCATION[1]	d (mm)[2]	Shape[3]	V_{min} (m/s)[4]	f[5]	h_{min} (m)[6]	Fr[7]	q (m^3/s)[8]
Flat Top Mountain -Cypress Hills	100	Equant	14	0.02	15	1.16	211
	150	Bladed	30	0.02	55	1.30	1,662

[1] Slope of study reach = 0.00385
[2] Dimension of intermediate diameter of largest particle in millimeters
[3] Shape of particle
[4] Minimum current speed in meters per second for particle transport in suspension
[5] Friction factor calculated using Keulegan Equation
[6] Minimum depth in meters to produce steady flow at minimum indicated current speed
[7] Froude Number
[8] Unit discharge in cubic meters per second per meter width

GENETIC INTERPRETATION

The indicated discharges are not typical of modern flash floods. As a comparison, the great flood of 1964 on the upper Missouri River resulted from a rainfall of 75 to 150 mm across the basin in a 36-hour period and the failure of dams to restrain the runoff [7]. Discharge of the Missouri River at Fort Benton, Montana (110°40'W, 47°49'N), was 2,192 m^3/s, or approximately 11 m^3/s per meter of channel width at a current speed of approximately 2.7 m/s. The minimum discharge values for the Cypress Hills and Flaxville Plain, respectively (Table 6), are three to six times this value **per meter width**. The area of the present Missouri Basin upstream of its confluence with the Milk River (see Figure 1 in [40]) is approximately 168,000 km^2. Assuming a drainage basin for the Flaxville "river" of 250,000 km^2 and a runoff coefficient identical to that of the upper Missouri basin, the amount of precipitation in 36 hours required to produce the minimum Flaxville discharge would be 115 to 230 mm. However, as pointed out above, this assumes a channel width identical to that of the Missouri River at Fort Benton (200 m) and a sinuosity of 1.0 for the Flaxville "river," a deposit not exhibiting characteristics of channelized flow.

Even this estimate, probably grossly below the actual discharge, indicates that modern flash flood analogues may be orders of magnitude too small to explain these deposits.

Large amounts of glacial ice could provide the necessary water for these discharges. Melting of roughly 15 m of ice per 24-hour period could provide all of the water necessary to meet the estimated minimum discharge requirements listed in Table 6. However, melting of 15 m of ice in 24 hours begs a term beyond "catastrophic melting!" Oard [38] has estimated melting rates of 7 to 18 m per year at the periphery of continental glaciers. One possibility would be damming of water behind ice, followed by failure of the ice dam. Jökulhlaups (glacial outbursts) tend to result in local floods that are quickly channelized [22, 23, 24]. Such a mechanism on a much larger scale has been proposed for the Spokane Flood postulated to have formed the channeled scablands of eastern and central Washington [3]. However, the Cypress Hills and Flaxville Plain differ markedly from the channeled scablands or modern glacial outwash terrains. Shaw et al. [57] have proposed catastrophic subglacial flooding of a magnitude comparable to that indicated from Table 6 to explain drumlins, flutes, and many other features in Saskatchewan and Alberta, though a means for generating floods of such magnitude is difficult to envision. Paleocurrent directions, lack of surface features, and the relationship of other benches are significant differences between the Cypress-Flaxville deposits and the features described by Shaw, et. al. [57].

The above calculations are conservative. They do not account for limitations of stream capacity, nor do they include estimates of erosional energy required to break up and remove the source rocks or shear off strata over enormous areas of the northern Great Plains. They do not account for the volumes of water and energy required to remove enormous volumes of sediments indicated by erosional remnants. That the gravel was itself an erosive agent is indicated by the presence of Ravenscrag concretions in the Cypress Hills Formation. The lack of subjacent lithologies elsewhere may result from their friable nature and the ease with which silt and clay particles can be transported relative to gravel. Lithification of the gravel to form conglomerates of the Cypress Hills Formation and Flaxville deposits resulted from the presence of calcium carbonate. If the lime cement originated with the abundant limestone in the presumed source area of the Montana Rockies, this indicates the limestone was almost completely pulverized or dissolved before reaching the Cypress Hills and Flaxville Plain. For glacial ice to provide the necessary water would require melting of roughly 15 m of ice per 24-hour period!

The flow conditions inferred for the deposition of the Cypress Hills Formation and Flaxville gravel are compatible with a diluvial interpretation. Strong currents could be expected to form as the land masses began to emerge during the latter part of the Deluge (Genesis 8:1-5). No hiatus need have occurred between the erosion of the enormous volumes of sediments from the area [40] and the formation of the Cypress Hills and Flaxville Plain. An origin in late diluvian time would explain the rapid formation of the erosion surfaces, the great transport distances of the gravels, the highly energetic currents, the huge discharges, and sheet nature of the deposits. These phenomena might be expected during the Recessive Stage of Walker's geochronologic paradigm [67] or the Upper Flood Division of Froede [15].

SUMMARY AND CONCLUSIONS

Based on the data and interpretations presented above, the following conclusions concerning the depositional origin of the Cypress Hills Formation and Flaxville gravel are presented:

- Planar, surficial erosion surfaces capped by gravel largely of exotic lithologies but containing minor amounts of subjacent lithologies implies formation of the erosion surfaces by corrasion due to highly energetic transport of the gravel from apparent source areas west and south of the Cypress Hills and Flaxville Plain.

- Attributes of the sediments are generally compatible with fluvial/traction current, turbidity current, and hyperconcentrated flow interpretations. On a sedimentological basis, the most likely process is the fluvial/traction current.

- Energy constraints preclude transport by a non-Newtonian flow process.

- Paleohydrologic analysis is not particularly sensitive to sediment loading when smectite clays (particularly montmorillonite) are absent. The Cypress Hills Formation and Flaxville gravel are lacking in fines. A Newtonian analysis is therefore appropriate.

- A Newtonian paleohydrologic analysis of the gravels/conglomerates indicates minimum discharges far in excess of modern floods or jökulhlaups, in excess of even the most catastrophic glacial outburst hypotheses.

The depositional environment inferred for the Cypress Hills Formation and Flaxville gravel is compatible with a diluvial interpretation. Deposition by regional currents in late diluvian time appears the most plausible genetic interpretation for these deposits.

ACKNOWLEDGEMENTS

We thank four anonymous reviewers and editor Steve Austin for their helpful comments.

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