BOULDER TRANSPORT ACROSS THE EBERSWALDE DELTA. A. D. Howard[1], J. M. Moore[2], R. P. Irwin, III[3], and W. E. Dietrich[4]. [1]Dept. Environmental Sciences, University of Virginia, P.O. Box 400123, Charlottesville, VA 22904-4123 (ah6p@virginia.edu), [2]NASA Ames Research Center, M.S. 245-3, Moffett Field, CA 94035, [3] Center for Earth and Planetary Studies, National Air and Space Museum, Washington, D. C. 20013-7012, [4]Dept. Earth & Planetary Sci., Univ. California, Berkeley, CA 94720.

Introduction: A recent HiRISE image (PSP_001336_1560) covers most of the Eberswalde delta [*1-6*] at a resolution of about 0.25 m/pixel. This image reveals local concentrations of boulders exceeding 1 m in size. The caption for this image (http://hiroc.lpl.arizona.edu/images/PSP/PSP_001336_1560/) suggets that the boulders "were likely too coarse to have been transported by water flowing within the channels" and suggests that the boulders are weathered fragments of lithified channel sandstones. We suggest that some of the boulder deposits are likely to be primary depositional features and that flows through the deltaic channels may have been competent to transport these boulders.

Image Analysis: The remarkable HiRISE image provides a level of detail nearly equivalent to a site visit. Boulder-size clasts are widespread across the deltaic complex. Some, as suggested by the image caption, are clearly weathered fragments from indurated fluvial/lacustrine delta deposits (Fig. 1). Where a source from indurated deposits is apparent, the fragments generally are angular and have a reddish cast, and the source bed commonly exhibits prismatic fracturing. A distinct type of bouldery deposit occurs on the delta surface, however, which may be primary depositional clasts. These boulders are light-toned, are nearly neutrally colored, and occur as patches and beds associated with major exhumed channels on the delta (Fig. 2). Locally these boulders occur as lenses of nearly uniform clast size. They are generally not found in extensive beds, and prismatic cleavage of an indurated source bed is not evident. Maximum clast size is about 2 m, and most visible clasts range from 1 to 1.5 m. Although the images are not definitive, they suggest a bimodal size distribution of the channel deposits, with the local boulder stringers being interbedded with reddish deposits of a grain size <0.5 m and, apparently, sufficiently fine to be readily wind-eroded.

Possible Origins of the Boulders: The boulders may either be of primary origin (that is, transported onto the delta at about the present size) or of secondary origin, either through weathering of indurated delta deposits (as suggested by the HiRISE image caption) or as concretions. The distinct coloration and bedding characteristics suggest a primary origin, however. Transport of primary meter-scale boulders onto the delta could occur through mass flows (e.g., mudflows) where transport is aided by the high density and viscosity of the transporting medium. The regular layering and well-defined, meandering distributary channels suggest that mass flows, if they occurred, were not the dominant transporting agent across the delta. The low gradient of the delta surface (~0.006, see below) also makes debris flow transport unlikely. The strong size sorting and local presence of thick beds (Fig. 2) of boulders suggest transport by ordinary fluvial flows. In the following analysis we apply sediment transport relationships to evaluate whether ordinary fluvial flows would be capable of transporting meter-scale boulders across the delta.

Fluvial Boulder Transport: The coarsest bedload fraction in rivers is typically transported only by flows that barely exceed the threshold of motion of the coarse fraction [*7, 8*]. The threshold of motion is generally expressed by a critical value, τ_{*c}, of the dimensionless shear stress, τ_*:

$$\tau_* = dS/\left(S_s - 1\right)D\,,$$

where d is channel depth, S is channel gradient, D is grain size, and S_s is sediment specific gravity. Thus transport of coarse debris is aided by steep channel slope, deep flows, or low sediment specific gravity. Although a low sediment specific gravity is a possibility, we explore transport of more typical rock with $S_s \approx 2.65$. The channel gradients across the delta sloped at about S=0.006 based on MOLA topography [*4*]. Estimates of discharge, Q, through the distributary channels based upon channel dimensions range from 650 to 1600 m^3/s [*1*] and a similar discharge range of 250–950 m^3/s was estimated based upon a numerical fan model [*4*]. Original channel width, W, was estimated by [*2*] to be about 50 m and by [*1*] to be about 100 m. Previous studies have generally assumed that the channels transported either sand or fine gravel (~0.01 m) [*1, 4*]. This size range is also consistent with the channel geometry [*9*].

Threshold of motion criteria. Estimates of critical values of τ_{*c} for gravel from both flume and field studies have been summarized in numerous studies (e.g. [*10-12*]). Critical shear stress depends strongly on grain size distribution, relative particle exposure, and bed geometry. Cited values range from 0.01 to 0.25, with most studies suggesting values from 0.03 to 0.08. Recent studies have shown, however, that for bimodal mixtures of sand and gravel,(or coarse and fine gravels [*13*]) τ_{*c} can drop to values of about 0.01 when sand coverage on the bed exceeds 20% [*14*] due to the greater ability of exposed boulders to roll over the smaller particles.

Estimating flow conditions for boulder transport. To check whether boulders might reasonably have been transported across the delta, we estimate values of flow depth, discharge, and width/depth ratio for bouders of D=1 m boulders for values of τ_{*c} of 0.05 and 0.01, S=0.006, S_s=2.65, and W=50 m. We assume fully rough flow and the following hydraulic relationships (e.g., [*15*]):

$$V = \sqrt{8gdS/f}\ ;\ f = 0.113\sqrt[3]{D_e/d}\ ;\ Q \cong WdV\ ,$$

where V is flow velocity, f is the friction factor, and D_e is the effective grain size for flow resistance. Two values of D_e are assumed, D_e=1 for boulder-controlled resistance and D_e=0.01 for fine gravel or bedform dominated flow resistance.

Table 1. Predicted flow depth, discharge, and width-depth ratios.[&]

τ_{*c}	0.01	0.01	0.05	0.05
D_e	1	0.01	1	0.01
d	2.75	2.75	13.8	13.8
Q	338	729	4947	10568
W/d	18.2	18.2	3.63	3.63

[&] Yellow cells are assumed values for τ_{*c} and D_e and blue cells are predicted values.

Boulder transport by normal fluvial flows on the delta would occur under reasonable values of flow depth, discharge and width-depth ratio if the critical dimensionless shear stress were near the low range of about 0.01 but would be unlikely if τ_{*c} were closer to its value for unimodal gravel-boulder beds of about 0.05 because the very high discharges would be inconsistent with other estimates of flow magnitude.

Conclusions: The boulder outcrops in the exposed channel deposits of the Eberswalde delta could be transported by normal fluvial flows if the bed material were strongly bimodial, with a dominant sand or fine gravel bed with a minority of coarse boulders. Under these conditions the observed patchy distribution of boulder deposits might be expected because chance accumulations of boulders might become stabilized and attract additional through-flowing boulders because the critical shear stress would increase where boulders dominate the bed.

A strongly bimodal sediment delivery to the delta might occur because most of the upstream contributing area is a low-relief uplands that would probably contribute primarily fine sediment. Just before emerging onto the fan, however, the main channel feeding the delta passes through a steep (S≈0.04) ~15-km canyon averaging about 60 m in depth that might supply the boulder component. Boulders 1 m in diameter can readily be entrained by flows <1000 m^3/s in such a steep canyon with τ_{*c} of 0.05.

Alternative explanations for the boulder component of the delta deposits include a secondary origin as weathered indurated layers or concretions, or through primary deposition via concentrated mass flows.

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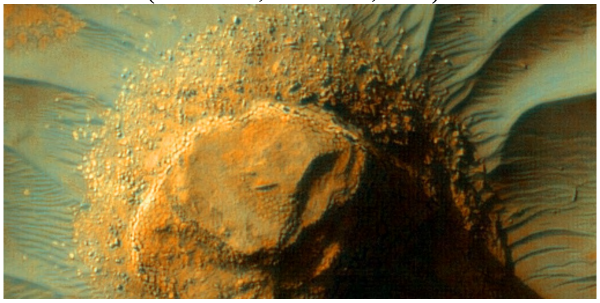

Figure 1. Blocky weathered boulders in Eberswalde delta deposits in sub-image from HiRISE PSP_001336_1560. Image width 128 m.

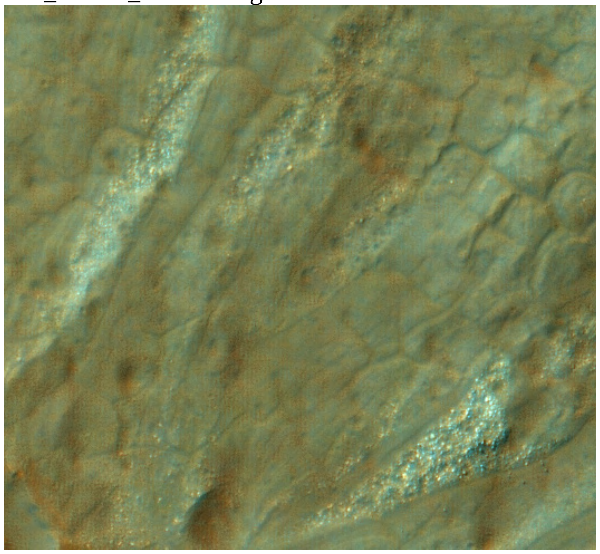

Figure 2. Gravel exposed in delta sediments in sub-image from HiRISE PSP_001336_1560. Image width 133 m.