Thresholds for sediment bypass by turbulent flows:
implications for stratigraphic trap and sand prediction in turbidite systems

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1) Introduction

A key theorem describing the evolution of all fluvial[1] and deep marine[2] sediment transport systems is that of accommodation as governed by erosion and deposition along the slope profile (**Fig. 1**). Erosion and deposition depend on if a flow is under- or overloaded, with the critical bypass criterion defined when net erosion/deposition is zero. This critical bypass criterion is used to define an equilibrium slope profile, towards which the system will evolve. Here this condition will be described in terms of the critical Shields bypass number (dimensional shear stress) for equilibrium flow.
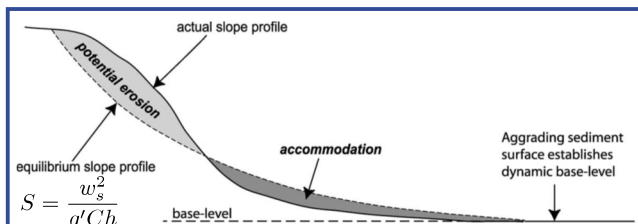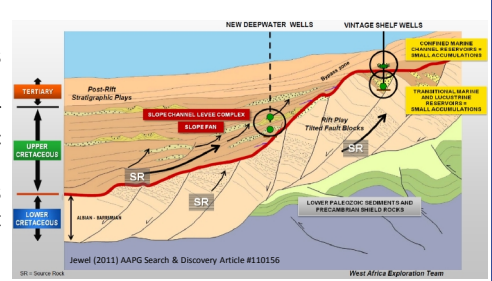
$$S = \frac{w_s^2}{g' C h}$$

Figure 1. Accommodation space and turbidity current equilibrium slope profile as a function of sediment bypass; modified after [2].

Importance to E&P

The equilibrium profile determines locations of deposition and erosion and therefore the 1) distribution of reservoir sands and 2) position of stratigraphic pinchout traps produced by a transition from erosion/bypass to deposition. This for instance is critical to the abrupt margin play model (right) reliant on 'upslope stratigraphic pinchout traps.

2) Flow Bypass Models

Existing bypass criterion are summarized in **Table 1**. Here a depositional-erosional flux balance criterion (**Fig. 2**) is used as it enables analysis of the effect of grain size distribution on sediment bypass (**§3**). A comparison of different model bypass predictions and observations, using mean observational parameters C=0.2%, c_d=15^{-2} and h=0.25 (**§4**), is shown in **Fig. 3**.

Table 1. Summary of widely used empirical and theoretical bypass (equilibrium suspended load) sediment transport models.

Figure 2. Type III depositional-erosional flow bypass schematic model for equilibrium suspended load sediment transport [3].
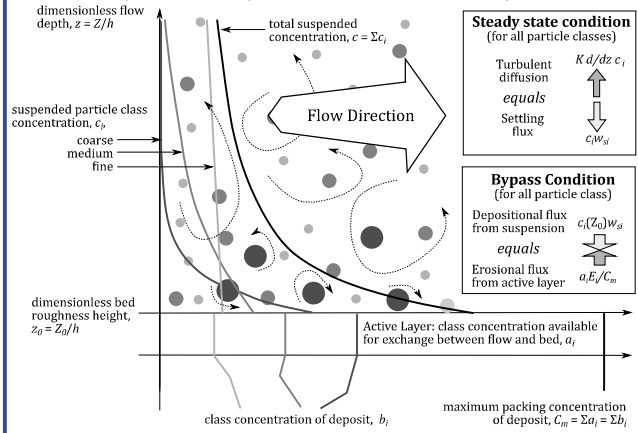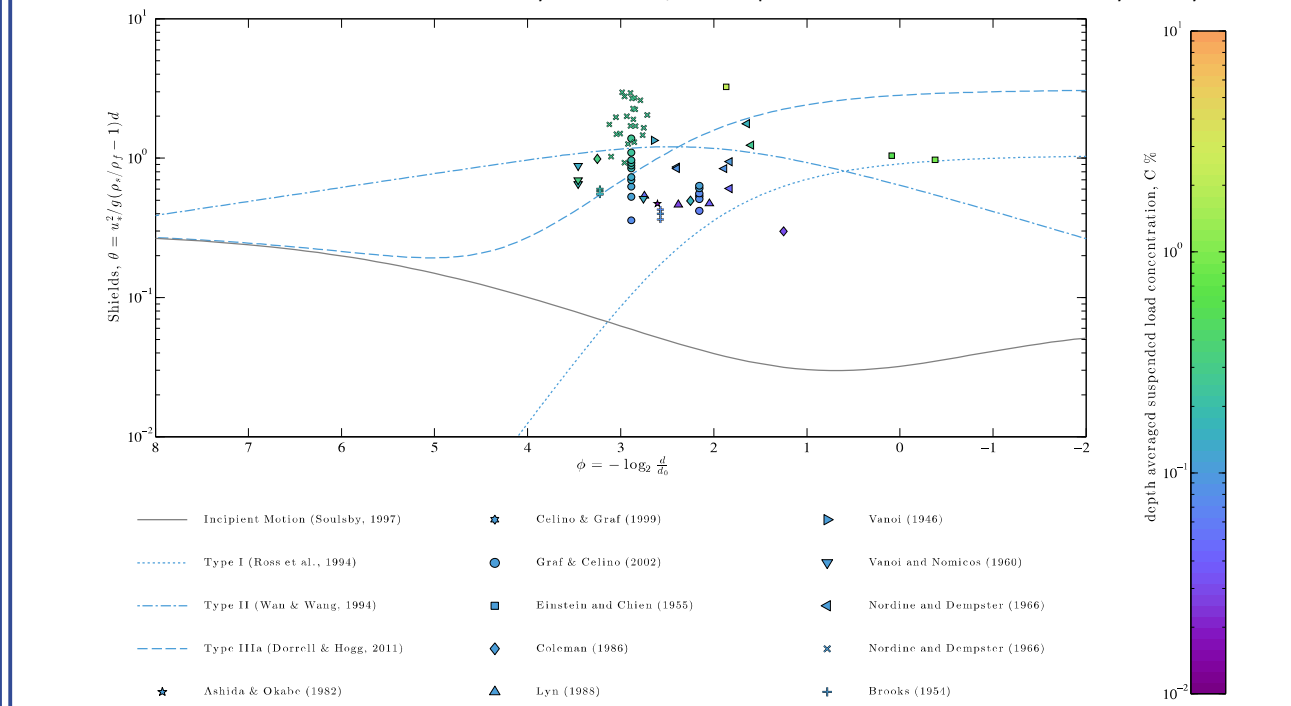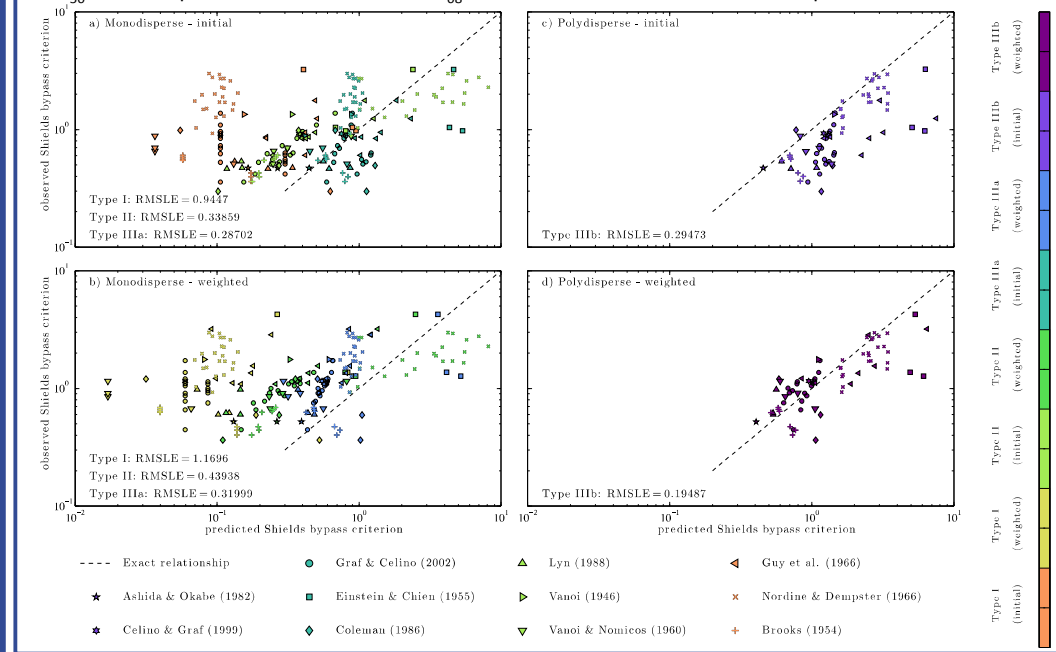

Figure 3. Shields bypass criterion predicted by the sediment transport models Type I (dotted curve), II (dash-dotted curve) and III (dashed curve), see **Table 1**. For a given suspended load and grain size, flows are net depositional below the criterion and net erosional above it. The Shields criterion for initiation of motion is denoted by a solid curve, whilst experimental observations are denoted by filled symbols.

3) Results for Polydisperse Flow Model

Real-world sediments have particles with a continuously varying grain size distribution. This may be approximated by a discrete, polydisperse, suspension of finite number of distinct particle classes [3]. Many real-world sediments are log-normally distributed (skewed towards finer grain sizes); using the polydisperse model IIIb the effect of such a grain size distribution on sediment bypass may be analyzed, see **Fig. 4**. Whilst an infinite log-normal grain size distribution is physically unrealistic, a truncated distribution of the central 99% of particle classes is used.

Figure 4. The Shields bypass criterion, using the polydisperse model IIIb, for fixed flow capacity C, (a)-(d) and for fixed log-normal grain size standard deviation σ, (e)-(h). In (a)-(h) the solid grey curve denotes Shields criterion for motion. In (a)-(d) the dashed black curve denotes the Shields bypass criterion for a monodisperse suspension, σ=0. In (c)-(h) red curves denote contours of constant near bed concentration, $c(Z_0)$.

4) Correlation with experimental and field based observations

The bypass models (**Tab. 1**) are compared against experimental and field observations of open channel flows (**Fig 5**). Results summarize use of both a monodisperse distribution, based on d_{50}, and polydisperse distributions, based on a skewed log-normal fit to initial and measured (or weighted) suspended grain size data.

Figure 5. (a)-(d) Correlation between predicted and observed Shields bypass criterion. For experiments weighted distributions reduce the mean grain size of suspended load material as a function of the initial distribution; here the d_{50} of the suspended load is taken as the d_{08} of the initial distribution based on empirical correlations.
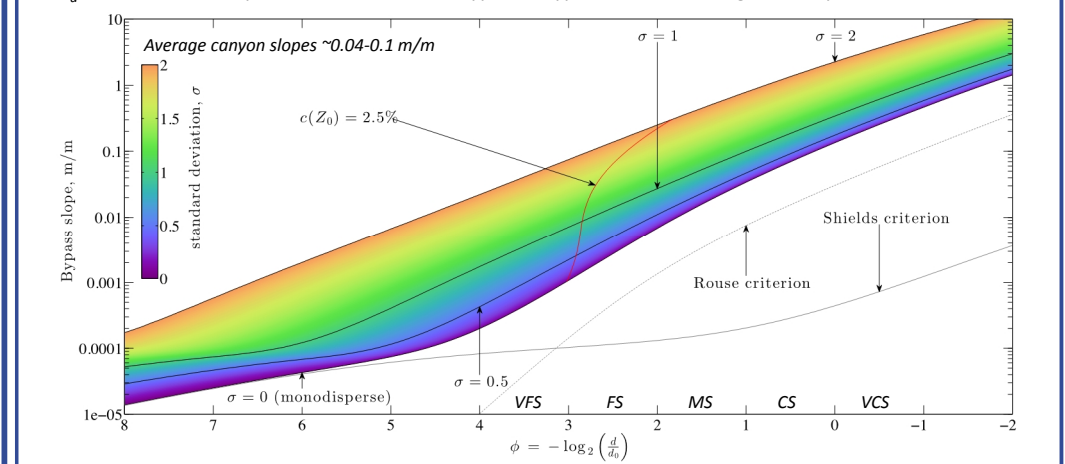

5) Implications for Turbidite Systems

For an equilibrium state turbidity current (with friction in balance with gravitational forces), where suspended load, flow height and drag coefficient are known, the Shields bypass criterion can be used to derive an equilibrium slope, S (**Fig. 6**). From [4] the equilibrium slope is defined in terms of bulk flow parameters:

$$S = \left(c_d + E\left(1 + \frac{1}{2}Ri\right) \right) Ri^{-1}. \quad (1)$$

Figure 6. The range of critical bypass slopes, derived from (1), for a 100m high turbidity current, where C=0.1% and c_d=20^{-2}. Flow velocity was derived from the Type IIIb bypass model with log-normally distributed sediment.

6) Conclusions

- **New polydisperse bypass model provides best fit with experimental observations.**
- **Bypass Shields criterion and bypass slope varies with sediment distribution and flow load.**
- **Stratigraphic pinchout traps more likely to form in fine-grained and well-sorted systems.**

References: [1] Gilbert, 1877, *USGS, Geology of the Henry Mountains*, Washington. [2] Kneller, 2003, *Marine and Petroleum Geology*, 20, 901–910. [3] Dorrell et al., 2013, *J. Geophysical Research: Earth Surface*, 118, 1939-1955. [4] Parker et al., 1987, *J. Hydraulic Research*, 25, 123–147.

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