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A quantitative model for deposition of thin fluvial sand sheets

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Abstract: Sheetfloods are typically invoked as the mechanism responsible for the kilometre-scale transport of sand-sized sediment grains in shallow-gradient fluvial systems. This concept is based on the lateral extent of ancient thin, sheet sandstone deposits rather than on fluid dynamics, which has resulted in a loosely constrained model for sheetfloods. This study tested the conceptual mechanism by developing a depth-averaged, 2D computational fluid dynamics model. The model results compare well against observations from modern deposits at Lake Eyre to provide a quantitative, physically sound basis for sheetfloods that can be applied in ancient and modern settings to constrain otherwise qualitative interpretations.

Fluvially sourced, thin, sheet sandstones and splays are frequently observed at the distal fringes of endorheic, shallow-gradient drainage basins in ancient (Stear 1983; Tunbridge 1984; Hirst & Nichols 1986; Olsen 1987; Dreyer 1993; Hinds *et al*. 2004) and modern settings (Parkash *et al*. 1983; Abdullatif 1989; Lang *et al*. 2004; Tooth 2005). Process interpretations suggest that subaerial, unconfined, sheetfloods were responsible for depositing sand-sized sediment over distances of hundreds to thousands of metres. The term sheetflood is used here in reference to subaerial, unconfined, turbulent flow events that undergo expansion, thinning and deceleration with increasing radial distance from source. This concept of unconfined, fluvially sourced sheetfloods is qualitatively based on observations and dimensional measurements of sheet sand deposits rather than on a firm understanding and appreciation of the fluid dynamics of sheetflood events. Using descriptional observations to interpret the physical processes of sheetflood events is an unsafe way to proceed (see Paola 2000), as the fundamental question 'what are the fluid dynamic characteristics of sheetfloods that are capable of transporting sediments over the distances interpreted in the literature?' remains unanswered. As a qualitative, descriptional concept, the relevance to both ancient and modern datasets is difficult to test and predictions regarding sedimentary deposits are very loosely constrained. This concept cannot easily be tested via laboratory modelling, as scaling of the thin sheetflood will result in laminar flow conditions. This paper compares the results of a 2D computer model for sheetfloods with observed data collected from the Douglas Creek Terminal Splay, central Australia, to provide a quantitative, fluid dynamics framework for fluvial sheet sandstone interpretation. In doing so we present a mathematical solution that generates well-constrained predictions that can be applied to and tested on analogous ancient and modern deposits.

Douglas Creek Terminal Splay

The terminal splay deposited from numerous sheetflood events at the terminus of the ephemeral Douglas Creek, Lake Eyre, central Australia (Fig. 1) was selected as a modern example of a sheetflood deposit. Thirty-one trenches were dug on the 4 km^2 splay at various measured distances up to 2 km from source at the channel mouth. Facies were described and thickness measurements and mean grain sizes recorded at each location. The splay sediments were classified into proximal, medial and distal splay based on their sedimentary characteristics as highlighted in Table 1. In the proximal regions coarse to medium, cross-bedded sands display thin (20–30 mm), basal gravel lags and occasional large (up to 80 mm in diameter) clay rip-up clasts. With increasing distance from the source channel, deposit thickness decreases, mean grain size fines and primary sedimentary structure is lost. The decrease in deposit thickness and grain size is interpreted to result from sheetflood deceleration and spreading with increasing distance from source. The loss of primary sedimentary structure with increasing distance from source is interpreted to predominantly represent a transition from bedload to suspension as the main depositional mechanism as a result of the decelerating regime. Evidence for destruction of primary sedimentary structure via pedogenic processes is present in the form of roots and shallow ($<$4 cm) cylindrical burrows but the sporadic concentration of these features suggests that bioturbation is not the principal reason for the lack of structure. The thickness and mean grain size of deposits at a given distance from the channel mouth provide two directly comparable measures with which to evaluate the computer model.

Computational fluid dynamics model

To investigate the processes involved in the kilometre-scale transport of sand-sized particles in a metre-scale thick sheetflood, we use equations modelling a turbulent, depth-averaged, steady-state, radial flow across a horizontal surface. These equations model a flow driven by momentum together with a pressure gradient (caused by the slope on its upper surface) and resisted by frictional shear stress at the flow base. The mathematical development is similar to that given by Waltham (2004) except that here we investigate the case of a radial, rather than linear, flow.

The starting equations conserve mass and momentum in steady-state radial flows and take the form

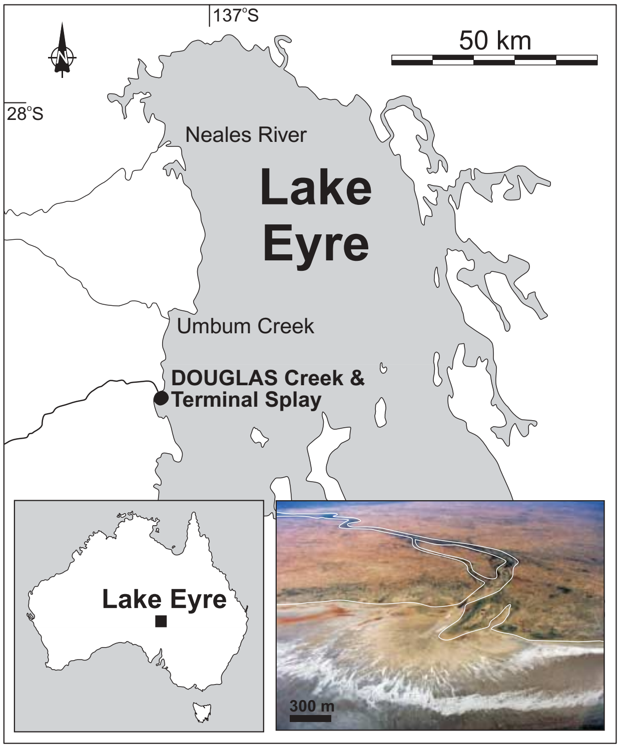

Fig. 1. Location and morphology of the Douglas Creek Terminal Splay, Lake Eyre, central Australia.

$$\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial z}=0 \tag{1}$$

and

$$u\frac{\partial u}{\partial r}+w\frac{\partial u}{\partial z}=-g\frac{\mathrm{d}h}{\mathrm{d}r}+\frac{1}{\rho}\frac{\partial \tau}{\partial z} \tag{2}$$

where u is velocity in the radial (r) direction, w is velocity in the vertical (z) direction, h is flow thickness, ρ is flow density, τ is shear stress in the radial direction and g is gravity. These equations can be depth averaged and combined provided a self-similar velocity v. height profile is assumed, i.e.

$$u(z)=f(z/h)u(h) \tag{3}$$

with f a slowly varying function of horizontal position and $f(1)=1.0$. The resulting equation is (see Waltham (2004) for derivation method)

$$\frac{\mathrm{d}h}{\mathrm{d}r}=\left(\frac{a\bar{u}^2h}{r}\right)-\frac{\tau}{\rho}/[gh-(2ab-b^2)\bar{u}^2] \tag{4}$$

where

$$\bar{u}^2=a\bar{u}^2 \tag{5}$$

and

$$u(h)=b\bar{u}. \tag{6}$$

It should be noted that a and b are constants of order unity. Their precise values depend upon the shape of the velocity v. height profile. For a turbulent flow we can assume the law of the wall (Duncan *et al*. 1960); that is,

$$\frac{uk}{u_*}=\ln(z/z_0) \tag{7}$$

with

$$\tau=-\rho u_*^2 \tag{8}$$

where k is von Karman's constant (*c*. 0.4), u_* is the shearing velocity and z_0 is the roughness scale. Depth integration of these expressions then yields $a=A/B^2$, $b=L/B$ and

$$\tau=\frac{-\rho k^2\bar{u}^2}{B^2} \tag{9}$$

where

$$A(h)=L^2-2L+2-2(z_0/h) \tag{10}$$

$$B(h)=L-1+(z_0/h) \tag{11}$$

and

$$L(h)=\ln(h/z_0). \tag{12}$$

In fact, for all reasonable flow depths and roughness scales, evaluation of these expressions shows that $a\sim b\sim 1$ is a good approximation and so equation (4) can be replaced by

$$\frac{\mathrm{d}h}{\mathrm{d}r}=\left(\frac{h\bar{u}^2}{r}\right)-\frac{\tau}{\rho}/(gh-\bar{u}^2) \tag{13}$$

with the shear stress determined from equation (9). It should be noted that this predicts a large slope when $gh\sim\bar{u}^2$ (i.e. a hydraulic jump when the Froude number approaches unity).

Table 1. *Sedimentary characteristics of proximal, medial and distal splay deposits as observed at the Douglas Creek Terminal Splay*

Location	Description	Distance from source (m)
Proximal splay	Erosional and planar based, coarse–medium, cross-bedded and massive sands; gravel lag and clay rip-up clasts are commonly seen	0–1000
Medial splay	Planar based medium–fine, massive sands; gravel lags and clay rip-up clasts are rare	800–2000
Distal splay	Planar and gradationally based fine to very fine, massive sands with high silt or clay content	⩾1500

The overlap of the deposits' distance from source reflects the asymmetrical propagation of flood events as a result of existing topographic features and a negligible slope gradient.

Results

Modelling of equation (13) for a given flux and initial velocity yields the distance at which a given grain size reaches its critical velocity for transport in suspension and bedload (Fig. 2). These thresholds were calculated using Shield's criterion (Allen 1997) for bedload and the Bagnold criterion for suspended load (Bagnold 1966). Figure 2 shows that thin, unconfined sheetfloods are a kilometre-scale transport mechanism for sand-sized sediment. With these parameters sheetflood events are capable of transporting coarse sands up to 750 m away from the feeder channel whereas fine sands reach critical bedload velocity at 1600 m from source. As grain size decreases and distance from source increases, the critical velocities of a given grain size for transport in suspension and bedload become closer and at a distance of 1800 m they cross over. The decrease in distance between critical velocities for suspension and bedload transport effectively relates to a decrease in the role of bedload transport as grain size fines and distance from source is increased. At the point of interception the critical velocity for bedload transport exceeds that of suspension. This means that for fine-grained sediments in the distal sectors of sheetflood events suspension replaces bedload transport as the dominant depositional mechanism. This is equivalent to the 'introduced' suspended sediment of Leeder *et al*. (2005).

Comparison between computer model and observed field data

Figure 2 shows that the sheetflood mechanism is physically reasonable but, to allow direct comparison between the fluid-dynamic model and field data, we need further equations governing the sedimentation rates. Using Stokes' law (Stokes 1851) the settling velocity (ω) of particles in suspension is given by

$$\omega = \frac{(\rho_p - \rho_f)gD^2}{18\mu} \qquad (14)$$

where ρ_p is the density of sediment particles, ρ_f is the density of the fluid, μ is the dynamic viscosity of the fluid and D is the particle diameter. For sediments to be transported in suspension the settling velocity for each grain size must be exceeded by the shearing velocity of the fluid, which is given by Bagnold's suspension criterion (Bagnold 1966). Sediments settle out of suspension at a rate ($\partial s/\partial t$) given by

$$\frac{\partial s}{\partial t} = c(\omega - u^*) \qquad (15)$$

where c is the concentration of a given grain size in suspension. This expression gives a sediment fall velocity equal to the Stokes' velocity when $u^* = 0$ and zero fall velocity when $u^* = \omega$. Multiplication of $\omega - u^*$ by concentration converts the fall rate into a deposition rate. Sediments that settle out of suspension are transferred into bedload and transported at a rate calculated using the bedload transport formula of Ackers & White (1973).

The model requires a number of flow (Table 2) and sediment (Fig. 3) input parameters to be defined. Channel width and initial flow depth (channel depth at terminus) have been directly measured from Douglas Creek. Surface roughness has been estimated from field observations, whereas initial velocity and flux have been determined by matching model output to the observed deposit thickness and grain size. The grain-size range has been

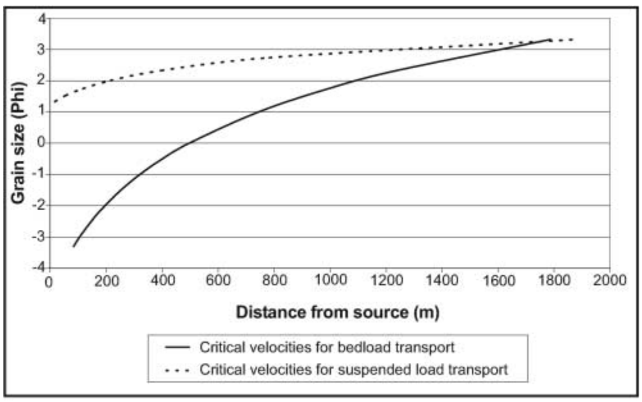

Fig. 2. Suspension and bedload transportation capacities for sheetflood events of similar scale to those that occur at the Douglas Creek Terminal Splay. Results are obtained from the computer model. The fluid flux and initial velocity used in this figure are taken from the input parameters used in the Douglas Creek comparison (see Table 2).

Table 2. *Values used as flow input parameters for computational fluid dynamics modelling*

Flow input parameter	Value
Channel width (m)	150
Initial flow depth (m)	2
Initial velocity (m s^{-1})	2
Surface roughness-element thickness (m)	0.01
Density of sediment (kg m^{-3})	2500
Porosity of deposited sediment	0

These parameters attempt to scale the computer model to realistic flow conditions that are representative to those at the Douglas Creek Terminal Splay. The initial velocity value used is reasonable based on observed and interpreted figures from flood events of similar magnitude (e.g. Ives 1936; Costa 1987; Kochel 1988).

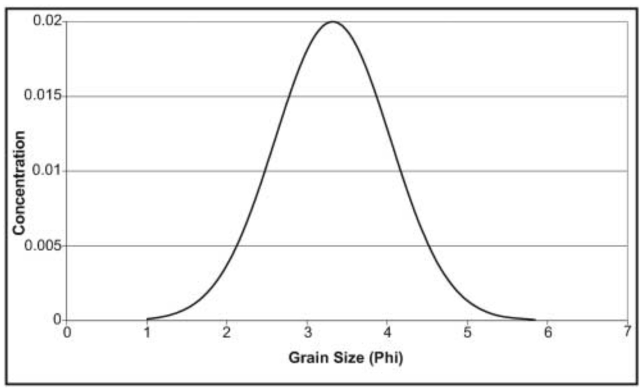

Fig. 3. Distribution and mean grain size of sediment transported and deposited, obtained from the computer model. Volume concentration is dimensionless; sediment concentration values between 500 and 34 000 mg l^{-1} would take between 18 days and 6.3 h to deposit the sediment thickness predicted by the computer model. The range in sediment concentration values reflects the range in observed measurements taken from ephemeral river systems (e.g. Bourke 2002; Alexandrov *et al*. 2003). The range in interpreted flood event length highlights the vast variability in the duration of ephemeral flow regimes (e.g. Knighton & Nanson 1997).

defined by measurements from the Douglas Splay sediments, whereas the concentration of sediment within the flow and flow duration have been obtained by matching the results to observed data (Fig. 3).

The model output for deposit thickness and mean grain size is compared against observed data from the Douglas Creek Terminal Splay in Figures 4 and 5. The initial increase in deposit thickness is observed from the surface topography in the field and in the model output. It is associated with the rapid deceleration and thinning of flow depth as the sheetflood becomes wholly unconfined. At this point of maximum deposit thickness the model indicates a mean grain size of 1.8ϕ, which compares well with the scatter of observed data at the same distance from the source.

The model and data indicate that deposit thickness steadily decreases to 2 cm at 2000 m and mean grain size decreases to 3.3ϕ. Scatter in the observed data reflects minor spatial variation in the nearly flat surface topography, which causes spatial variation in the flow regime and hence depositional response.

Application as a predictive tool

Figures 4 and 5 demonstrate how this quantitative approach to modelling can be used to constrain predictions regarding sheetflood deposit thickness and mean grain size with increasing distance from source. In both figures the model has used observed measurements at set distances from source to correctly scale the fluid dynamics computer model. The computer model has successfully interpolated results between these points and extrapolated the trend beyond the dataset.

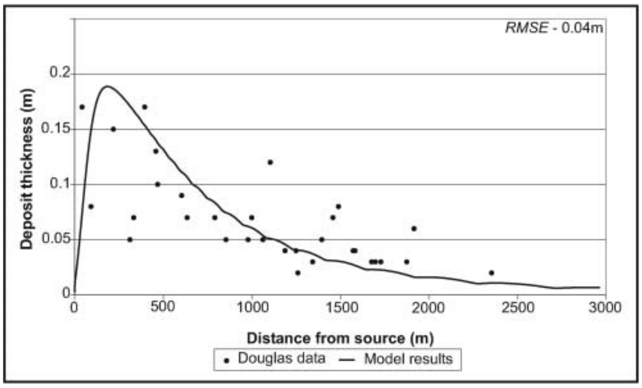

Fig. 4. Comparison of deposit thickness v. distance from source for the observed dataset from Douglas Creek and the predicted results from the computer model. The uneven result produced by the computer model results from the deposition of individual grain sizes. RMSE, root mean square error.

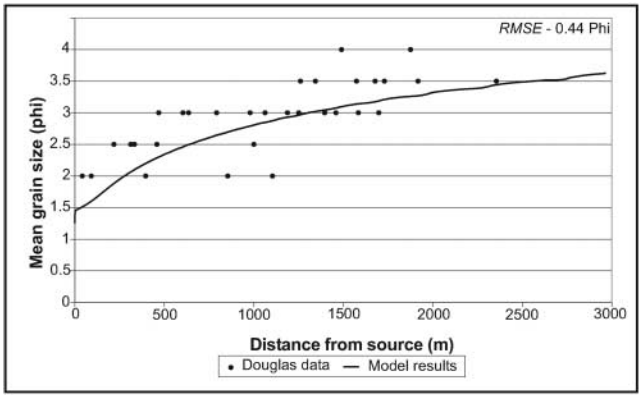

Fig. 5. Comparison of mean grain size deposited v. distance from source for the observed dataset from Douglas Creek and the predicted results from the computer model. RMSE, root mean square error.

In applying this technique to thin, fluvial sheet sandstones specific consideration must be given to whether the deposit being modelled aligns well with the model assumptions. First, the model is for unconfined sheetfloods that spread from a river mouth and is therefore driven by momentum and cannot be applied to lateral channel floods (see Nicholas & McLelland 1999). Flow is modelled over a flat surface of uniform roughness so the ponding effect of natural systems is not taken into account, which is why the model is seen to predict a coarser deposit in the distal sectors relative to observed data (Fig. 5). Finally, the sheetflood is modelled as a turbulent, dilute flow and the sediment transport criteria used are seen to match well with experimental data for grain sizes of 1 mm (0ϕ) or less (Allen 1997).

Conclusions

(1) This investigation has shown that fluvially sourced sheetflood events in shallow-gradient settings are a physically plausible mechanism for the kilometre-scale transport of sand-sized sediments.

(2) This study quantifies previous qualitative interpretations of analogous fluvial sheet sandstones and provides a quantitative, fluid dynamics framework for future observations.

(3) This quantitative, fluid dynamics approach to modelling sheetfloods has an application as a predictive tool for constraining deposit thickness and mean grain size in thin fluvial sheet sands.

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