

PS Estimation of Source-To-Sink Mass Balance by a Fulcrum Approach Using Channel Paleohydrologic Parameters of the Cretaceous Dunvegan Formation, Canada*

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Abstract

Trunk rivers transport the bulk of the sediment in a source-to-sink (S2S) system, and total mass passing through any cross section (i.e., fulcrum) of a trunk river over geologic time should allow matching of source area sediment delivery budgets, to the downstream sediment volumes deposited in the basin. We analyze the paleohydrology of ancient trunk channels and linked downstream deltaic strata of Allomember E of the Cretaceous Dunvegan Formation in the Western Canadian Sedimentary Basin to test the total mass balance fulcrum approach. Bankfull channel depth and width, grain size, paleoslope, velocity, and discharge are derived from outcrop, core, and well logs. Some parameter estimates use multiple methods providing a range of values and serving as a cross check of independent methods. Annual flood frequency and paleodischarge estimates, associated with long-term geologic time estimates, are derived from chronostratigraphic analysis and allow cumulative sediment discharge calculation. Isopach maps are used to estimate sink area sediment volumes. The results indicate that the trunk river of Allomember E was 10-20m deep and 150-250m wide, carried fine to medium-grained (average 180 microns) sand and flowed over a low-gradient paleoslope of 10^{-5} . Annual total sediment discharge is estimated to range from 2.6×10^6 to $8.4 \times 10^6 \text{ m}^3$. Within 70,000 to 100,000 years, the river is estimated to have transported $1.83 \times 10^{11} \text{ m}^3$ – $8.39 \times 10^{11} \text{ m}^3$ of sediment into the basin. This is consistent with the $1.1 \times 10^{11} \text{ m}^3$ of sediment documented in the sink area. However, the upper range estimate of sediment delivered into the sink is up to 8 times the measured sediment volumes, which, if accurate, suggests significant sediment escape. This supports the hypothesis that in Dunvegan time, mud was widely dispersed southward, along the Alberta Foreland Basin by geostrophic currents associated with storm processes and counterclockwise oceanic gyres in the Cretaceous Seaway.

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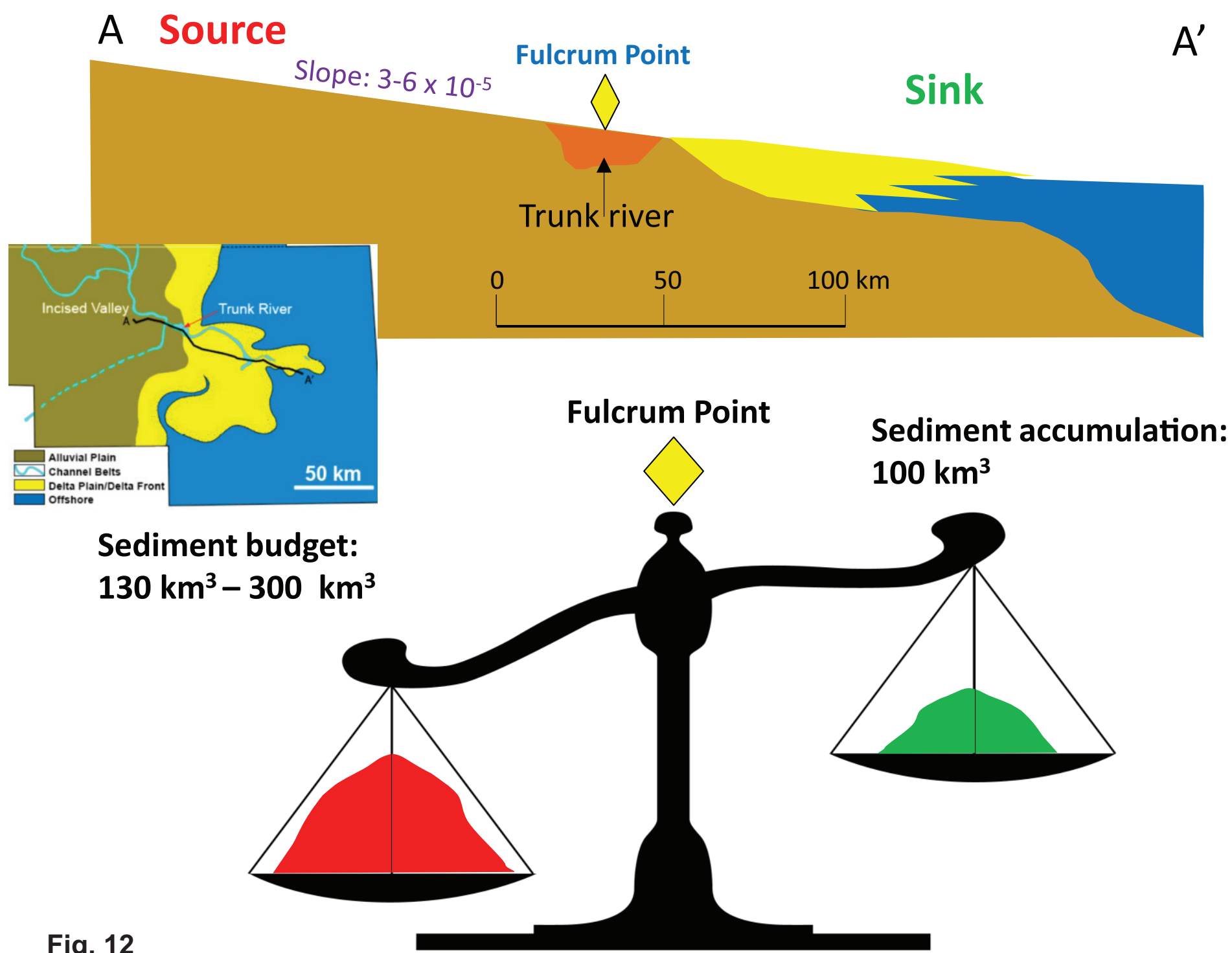


Fig. 12

Figure 12. Cross section of the S2S system and mass balance diagram. AA' profile is sketched cross sectional view of trunk river longitudinal profile of Parasequence E1 in Allomember E, referred to inset map of Parasequence E1 paleogeography. The trunk river serves as a fulcrum connecting source and sink. The estimated sediment volume delivered and passed through the fulcrum is ca. $130 - 300 \text{ km}^3$, while the documented sediment volume transported through the trunk river and accumulated in the sink area is about 100 km^3 . The sediment budget and accumulation volumes are in the same order of magnitude, which indicates a total mass balanced within the S2S system, while the upper range estimate of sediment delivered into the sink is up to 3 times the measured sediment volume, which is expected as the effects of sediment transient storage along sediment routing system, as well as a sediment post-deposition escape.

Discussion

The Mass Balance

The upper range estimate of sediment delivered from the source is 3 times the measured sediment volume in the sink area, which if accurate, would suggest significant sediment escape (Bhattacharya et al., 2016).

This supports the hypothesis that in Dunvegan time, mud was widely dispersed southward along the Alberta Foreland Basin by geostrophic currents associated with storm processes and counterclockwise oceanic gyres (see Plint et al., 2009).

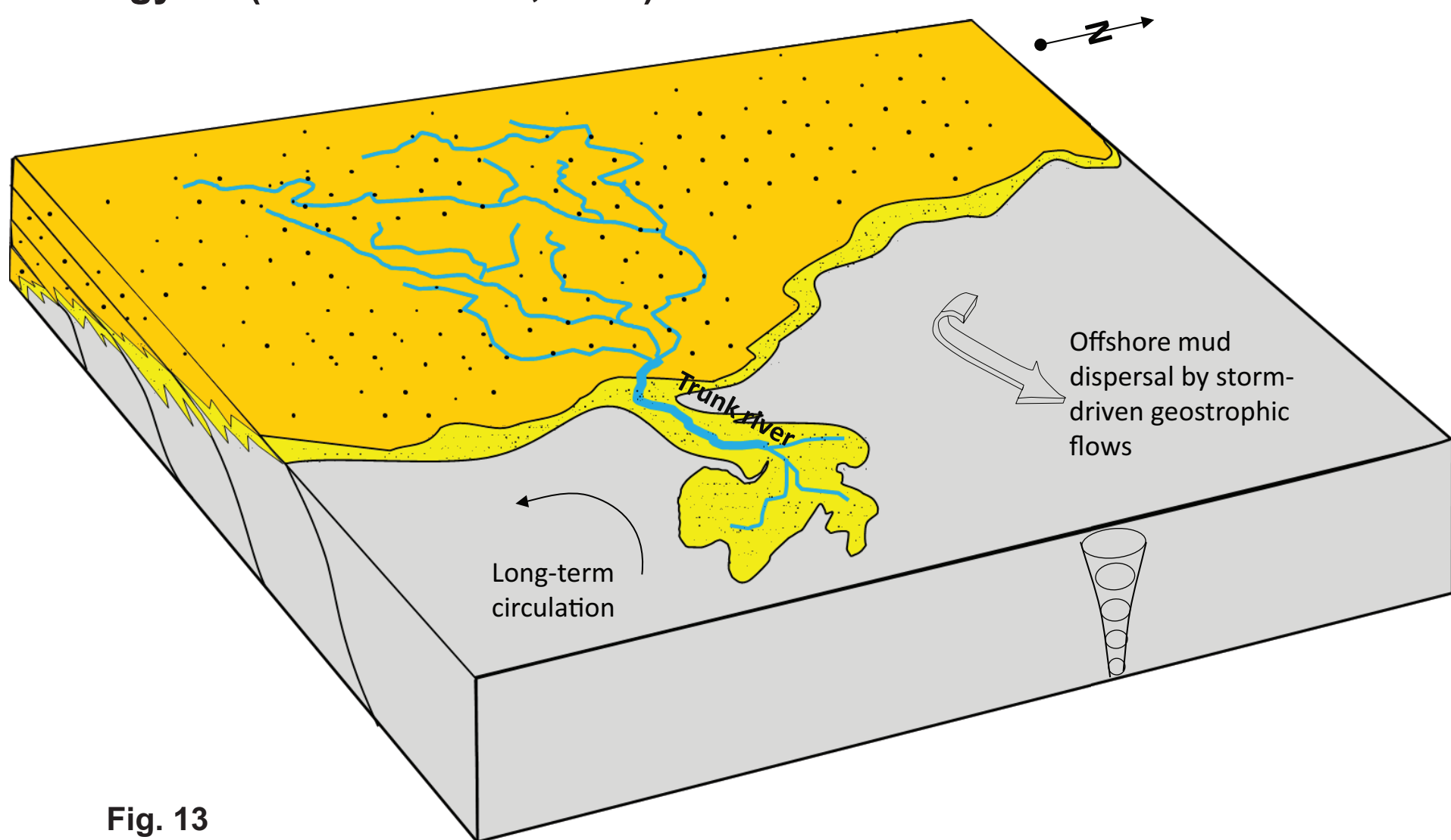


Fig. 13

Figure 13. Block diagram of paleogeographic map of Parasequence E1 in Allomember E, Dunvegan Formation with oceanic circulation initiated Gyre flows and storm-driven geostrophic flows illustrates the mud dispersal mechanisms along the shelf, which interpreted the potential sediment escape and a larger sediment volume from source area than the measured sediment volume preserved in the sink. The block diagram is based on the paleogeographic map in Bhattacharya and MacEachern (2009).

Paleodischarge and Sediment Volumes Estimations

Paleodischarge of the ancient trunk river was estimated to be in the range of $1.5 - 3.5 \times 10^3 \text{ m}^3/\text{s}$ and this is in agreement with the discharge of the Rhine River (approximately $3.5 \times 10^3 \text{ m}^3/\text{s}$), which represents a likely modern analogue for the Dunvegan trunk river as is also suggested by Davidson and North (2009).

The bedload in the trunk river of Allomember E is about 3 % of the total sediment load, suggesting low shear stress due to the low gradient. This may also indicate that a significant amount of sandy sediments were transported as suspended load.

The correlations between estimated drainage basin area and sediment load and sediment yield suggests that the Dunvegan E1 trunk fluvial system may be categorized as a moderate-sized mountain river drainage system (Milliman and Syvitski, 1992).

Table 2. Estimated drainage basin areas, sediment loads, and sediment yields for the trunk river of Allomember E					
Channel	Drainage Basin Area ($\times 10^6 \text{ km}^2$)	Sediment discharge ($\times 10^6 \text{ m}^3/\text{s}$)	Sediment Load (Mt/yr)	Sediment Yield ($\text{t}/\text{km}^2/\text{yr}$)	Remark
E1	0.14 – 0.18	5.2 – 11.9	12.5 – 28.6	89.3 – 158.9	Moderate-sized mountain river

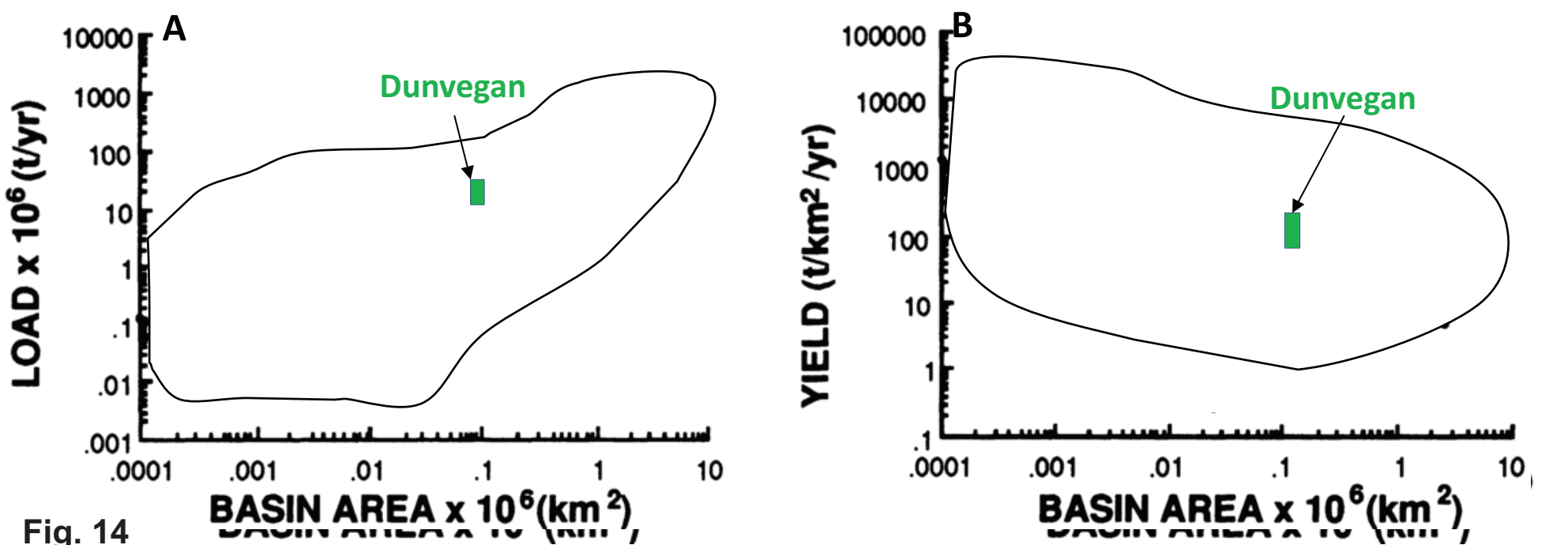


Fig. 14

Figure 14. A. Sediment load vs. basin area; B. Sediment yield vs. basin area of the global river database. Note the strongly normal trend between sediment load and basin area, whereas the generally inverse relationship between yield and basin area (modified Milliman and Syvitski, 1992).

Comparison to BQART Method

$Q_s = 0.02BQ^{0.31}A^{0.5}RT$, and $B = IL(1-T_E)E_h$ (Syvitski and Milliman, 2007)

Q - discharge, A - drainage area, R - relief, T - temperature

I - glacier erosion factor ($I \geq 1$), L - average basin-wide lithology factor, T_E - trapping efficiency of lakes and man-made reservoirs, E_h - human-influenced soil erosion factor

The estimated sediment discharge using the BQART formula ranges from 5.2 to $7.6 \times 10^6 \text{ m}^3/\text{s}$, the lower end of which is the same as the lower range of the annual sediment discharge estimated by the fulcrum method, and the upper limit is about 60 % of the upper range estimate using the fulcrum method, which may be ascribed to the use of an underestimated temperature (20°C) (Slingerland et al., 1996).

Errors and Uncertainties

The fulcrum approach involves a number of uncertainties, including field measurements, numerical assessments used to estimate paleohydrologic parameters, paleomorphodynamics derived from stratigraphic records, applicability of empirical equations, chronologic estimates, and modern analogue data selection. The integration of these variables constrain the accuracy of sediment volume estimation to at worst, one order of magnitude (see discussion in Holbrook and Wanas, 2014; Hajek and Wolinski, 2012; Bhattacharya et al., 2016).

The most sensitive error is related to annual discharge estimate, and can show an error of an order of magnitude.

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