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 2.6×106 to 8.4×106 m³. Within 70,000 to 100,000 years, the river is estimated to have transported 1.83 × 1011 m³ – 8.39 × 1011 m³ of sediment into the basin. This is consistent with the 1.1×1011 m³ 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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and Wadsworth, 2003).

Fig. 10

Introduction

The total sediment volume produced from the catchment should match the volume accumulated in downstream sinks in an ideally closed Source-To-Sink (S2S) system.

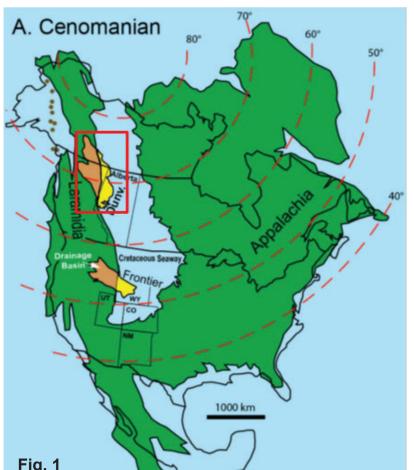
The total mass passing through any cross section over a given time should match both the sediment delivered from the catchment and the sediment volume passing forward to the sink.

The cross section in the sediment routing system acts as a 'fulcrum' The largest-scale incised trunk rivers and serve as key fulcrum points.

The fulcrum approach requires calculating the instantaneous paleodischarge and other paleohydraulic parameters of trunk rivers and integrating this over the durations of the associated stratal record of a given S2S system.

This approach does not require knowing source area properties and does not require a closed downstream basin; it enables estimates of catchment areas and relief, amount of sediment transported in the systems, and the volume of sediment accumulation in the basins.

This research estimated total mass balance through fulcrum analysis of trunk river deposits, and downstream sediment accumulation in the Upper Cretaceous Dunvegan Alloformation, in the Alberta Foreland Basin, Canada using a combination of outcrop and subsurface data.



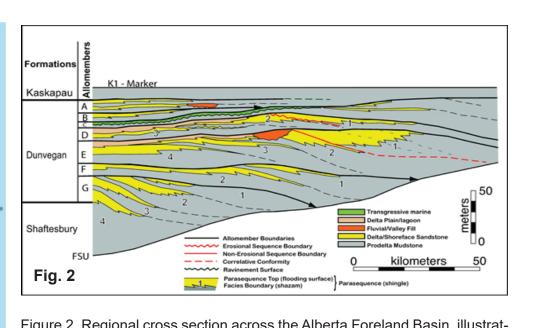


Figure 2. Regional cross section across the Alberta Foreland Basin, illustrating the allostratigraphic interpretation of the Upper Cretaceous Dunvegan Formation (Bhattacharya and MacEachern, 2009).

Figure 1. Cretaceous Cenomanian paleogeographic map of North America showing delta complexes of the Dunvegan Formation in Alberta (modified after Bhattacharya and MacEachern, 2009).

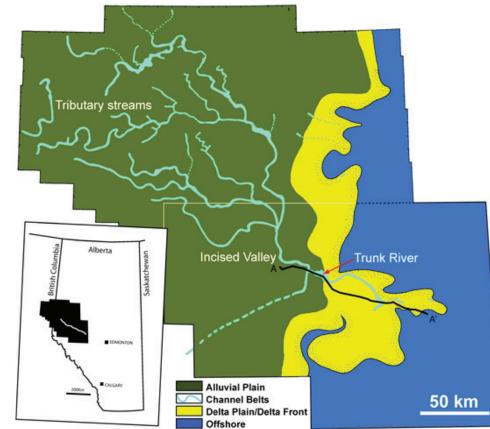


Figure 3. Paleogeographic map of valleys and lowstand deltas in Allomember E of the Dunvegan Formation (modifed after Bhat-

tacharya and MacEachern, 2009 and Plint and Wadsworth, 2003).

Allomember E:

The clearest linkage between the tributary drainage system and its lowstand delta deposit;

Fluvial-dominated delta system, with minimal tidal influence and limited wave reworking;

Previous mapping of the well-developed lowstand river-dominated delta volumetric estimation of the downstream sediment accumulation.

Methodology

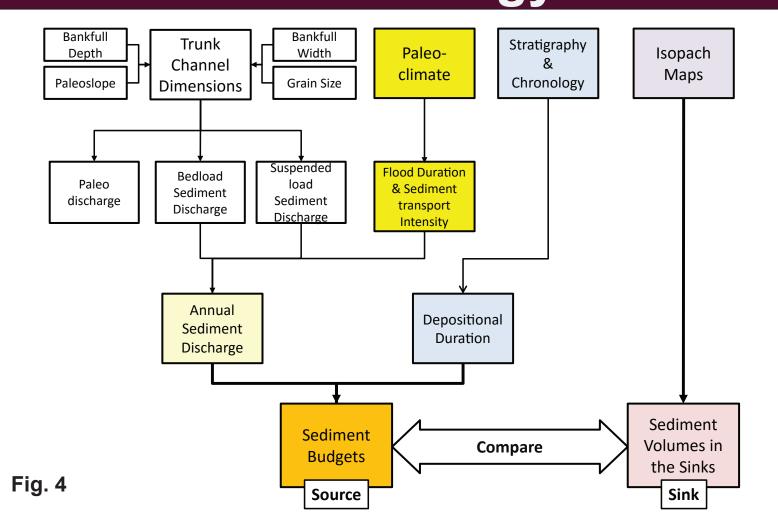


Figure 4. Work flow for fulcrum analysis

Trunk River Dimensions

Trunk River Bankfull Depth:

Measured in outcrops, cores or well logs with a small correct tion for compaction:

Sedimentary structures - dune-scale cross-bedding and accretion deposits.

Trunk River Width:

Empirical equation: w_c=8.8 d_m^{1.82} (single thread)

Grain Size: Core and thin section data

Paleoslope:

 $T^*_{bf50} = (H_{bf}S)/(RD_{50}) = constant -$ Backwater length: L_b=H_b/S

Average Flow Velocity:

Ū=C₂(RS)^{1/2} ----

Annual Sediment Discharge Estimation

 $Q_{mas} = Q_{ths} \times D/b$

where Q_{mas} is annual discharge, Q_{ths} is bankfull discharge, D is peak flood duration (days), and b represents the percentage of Total depositional duration of individual parasequences of total sediment transported during peak flood.

The flood duration and the proportion of sediment volume transported during flood events were estimated by reconstructing paleoclimate conditions and classifying paleoclimate regimes, compared to the Köppen-Geiger climate classification for modern systems.

Paleodischarge Estimation

Bankfull paleodischarge (Q_s), bedload sediment discharge (Q_{thf}) , suspended load sediment discharge (Q_{ss}) $C_{f}[(Q_{hf}^{2})/(B_{hf}^{2}H_{hf}^{2})]=gH_{hf}S$ ---

where C_i is the dimensionless Chezy friction coefficient, esti-

 $C_{f}^{-1/2}=(8.32)(H_{h}/k_{g})^{1/6}$ Measured from outcrops oriented perpendicular to the flow di- where $k_a = 3D_{ada} + 1.1\Delta(1 - e^{-25\psi})$, and $\Delta =$ bedform height = $H_{\rm hf}/8$ and $\psi=\Delta/\lambda$, where λ is bedform wavelength=7.3 $H_{\rm hf}$ (after

 $Q_{tbf} = B_{bf} q_{tbf} = B_{bf} (RgD_{50})^{1/2} D_{50} \alpha_t [\phi_s T^*_{bf50} - T^*_c]^{nt} - ----(4)$

 $\alpha_{*}=\alpha EH/C_{*}$, $\alpha EH=0.05$, $n_{*}=2.5$, $\phi_{*}=1$, $\tau^{*}=0$ where R is hydraulic radius, calculated by Equation (5).

 $R=A/P=(w_{o} \times d_{m})/(2 \times d_{m}+w_{o})$ -----(5)

where we is channel width and dm is channel depth. q = Fūd c -----(6); Q = q (w) ----where F is the suspension factor, ū is mean flow velocity, d_m is mean bankfull flow depth, and cois the concentration of suspended sediment at the reference depth.

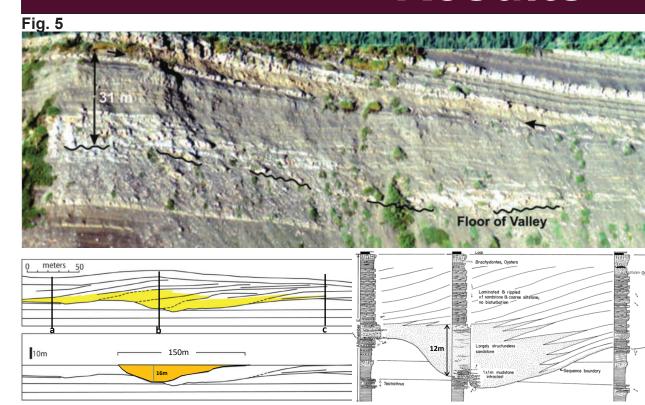
Cumulative Sediment Load

Allomember E was estimated by previous sequence strati-

Sediment Accumulation in the Sink

The total sediment volume deposited downstream of the trunk river was estimated using previous maps of Allomem-

Results



n outcrop, Inclined Heterolithic Stratification (IHS) of point bar deposits within the valleys indicates a 12 m deep channel that is about 100 - 150 m wide (Plint and Wadsworth, 2003).

Bhattacharya et al. (2016) estimated the tributary channel of the Allomember E trunk river to be about 16m deep and 150 m wide, based on lateral accretion bar heights from outcrop.

Figure 5. Large bar-scale lateral accretion observed from outcrops allowing facies bedding analysis, which can further infer channel dimensions (Bhattacharya et al., 2016).

stone, coal, paleosol. The average valley fills are 20 – 30 m thick, and valley widths are estimated to range from 0.5 km to Channel depth within the Allomember E valley was estimated to be 10 m as measured from core. Figure 6. Paleovalley of the Dunvegan Formation characterization and architecture correlation from outcrop indicating valley fill

Compilation of these mean channel depth values, estimated from multiple methods, suggests mean bankfull channel depth values of about 10 - 15 m.

Estimated trunk river channel width to range from 150 - 230 m:

Figure 7. Core description of Allomember E illustrates multiple-storey fluvial architecture and sedimentary structures within

valley fill succession. Single channel depth can be estimated to be about 10m. Cross-set is about 0.5m thick (modified after Plint

Trunk river width should be a small fraction of valley width.

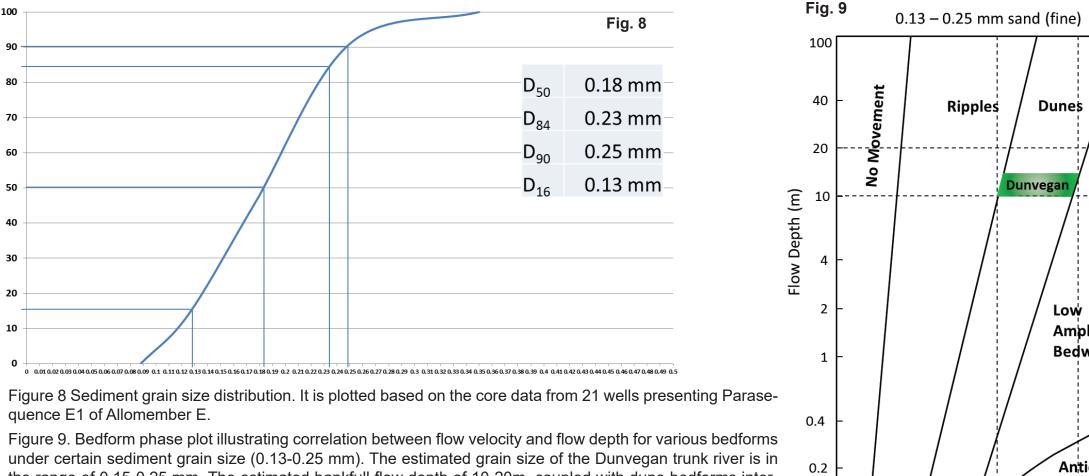
Single thread meandering characteristics and a low gradient suggest the entrenchment ratio should be greater than 2.2 (Rosgen, 1997), and accordingly the channel width should be less than 230 m.

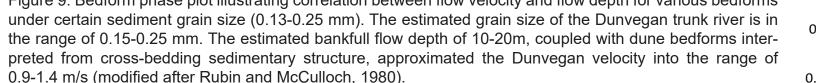
Trunk river must be somewhat wider than upstream tributary channels (100 - 150 m wide; Plint and Wadsworth, 2003)

Paleoslopes estimated from the equation are $3.7 - 5.5 \times 10^{-5}$

Microtidal to low mesotidal regime and the bayline limit of Allomember E (the order of 10's of km) suggests the same order of paleoslope estimate.

Tidal backwater length also suggests estimated paleoslope should be on the order of 10⁻⁵.







0 25 50 75 100 125 ₁₅₀ 175

Figure 10. The global climate zone classification of the Cenomanian

period. The Dunvegan deltaic complex was located in the Northern

nid-latitude warm humid zone (NMW) (modified after Hay and Floegel,

Velocity (cm/sec)

Bhattacharya, 1993)

The trunk river may transport 10 – 40 % (average 25 %) of the total suspended sediment within 2 % of the discharge time.

Figure 11. Plot of percentage of total suspended load discharged within 2% time of a year by rivers with various

Annual Sediment Discharge Estimation

 $10^5 - 1.17 \times 10^6 \,\mathrm{m}^3$.

Depositional Duration

tigraphic units	Years	Remark
al Depo. Duration of Dunvegan Fm.	2 million years	
ation of each allomember	200,000 years	10 allomembers
ositionally active duration	100,000 years	Valley incision time
ation of Darassaulanes E1	2F 000 voors	1 paracaguancas

 $Q_{mas} = Q_{ths} \times 7.3 / 25 \%$ The calculated annual bedload discharge is $1.65 - 2.53 \times 10^5$ m³, and the calculated annual suspended load discharge is $5.03 \times$

	Table 1. Paleohydrologic parameter and discharge estimates from the Dunvegan Formation Allomember E													
Ch	annel	Bankfull Channel Width (m)	_		Grain size (D ₁₆ , D ₅₀ , D ₈₄ , D ₉₀) (mm)	Q _{bf} Water (m³/s)	Q _{tbf} Bedload (m³/s)	(m/s)	Bankfull Suspended- Load Discharge, Q _{ss} (Van Rijn, 1984) (m³/s)		Suspended	Total Bedload Q _{tsb} (km³)	Total Suspended load Q _{tss} (km³)	Total sedime load Q (km³
-1	Min.	150	10	0.000055	0.15, 0.18, 0.23, 0.25	1523	0.07	0.95	2.01	165,154	5031,784	4.1	126	130
1	Max.	230	15	0.000037	0.15, 0.18, 0.23, 0.25	3503	0.10	0.96	4.63	253,280	11671,811	6.3	292	300

Sediment Accumulation in the Sink and Mass Balance

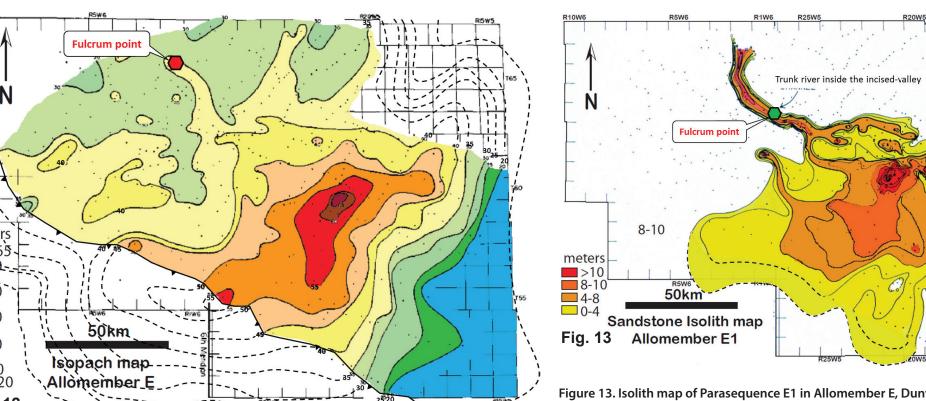


Figure 12. Isopach map of Allomember E in the Dunvegan Formation, Alberta, Canada. This wel depicts depositional configuration and progradational characteristics of Allomember E. The map is used for volumetric assessment of sediment accumulation down-dip to the fulcrum point. Dash lines were extended to close contours based upon geometric trend (modified after

igure 13. Isolith map of Parasequence E1 in Allomember E, Dunvegan Formation. The map well portrayed the lobate feature of river-dominated deltaic deposition. Sand-prone distributary system and deltaic lobes are depicted from the map. The map also allows sandy sediment volume calculation of the Dunvegan delta deposited in Parasequence E1. Dash lines were extended from original contours based upon deltaic lobate geometric trend (modified after Bhattacharya, 1993).

Stratigraphic units	Volume	Remark
The total volume of deposition in the basin down-dip of the fulcrum point	3.5 x 10 ¹¹ m ³	
The total volume of sediment deposited in the basin	2.8 x 10 ¹¹ m ³	assuming 20% average porosity
The original uncompacted sediment volume prior to compaction	3.1 x 10 ¹¹ m ³ (310 km ³)	10% compaction factor
Parasequence E1	1.0 x 10 ¹¹ m ³ (100 km ³)	assuming E1 accounts for one third of the total sediment volume of Allomember E
The estimated sandstone volume	3.2 x 10 ¹⁰ m ³ (32 km ³)	
Sand sediment volume	2.6 x 10 ¹⁰ m ³ (26 km ³)	assuming 20% average porosity

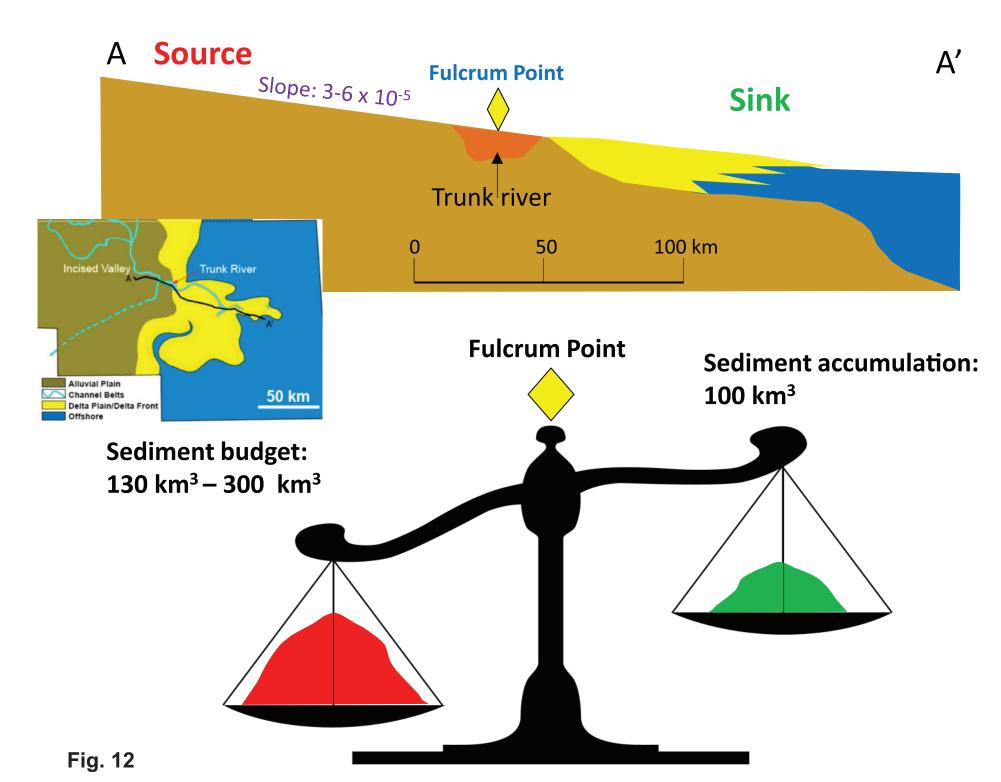


Figure 12. Cross section of the S2S system and mass balance diagram. AA' profile is sketched cross sectional view of trunk river longitudinal profile of Parasequence E1 in Allomember E, referred to inset map of Parasequence E1 paleogeography. The trunk river serves as a fulcrum connecting source and sink. The estimated sediment volume delivered and passed through the fulcrum is ca. 130 - 300 km3, while the documented sediment volume transported through the trunk river and accumulated in the sink area is about 100 km3. 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).

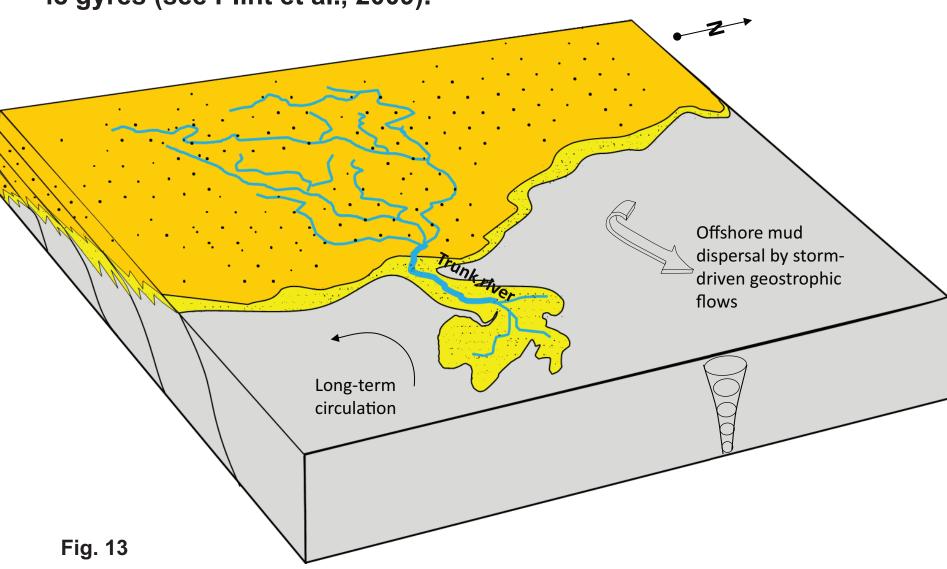


Figure 13. Block diagram of paleogeographic map of Parasequence E1 in Allomember E, Dunvegan Formation with oceanic circulation initiated Gyre flows and storm-driven geostrophic flows illustrates the mud dispersal mechanisms along the shelf, which interpreted the potential sediment escape and a larger 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 $1.5 - 3.5 \times 10^3$ m³/s and this is in agreement with the discharge of the Rhine River (approximately 3.5×10^3 m³/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 (×10 ⁶ km ²)	Sediment discharge (×10 ⁶ m ³ /s)	Sediment Load (Mt/yr)	Sediment Yield (t/km²/yr)	Remark			
E1	0.14 - 0.18	5.2 – 11.9	12.5 – 28.6	89.3 – 158.9	Moderate-sized mountain river			

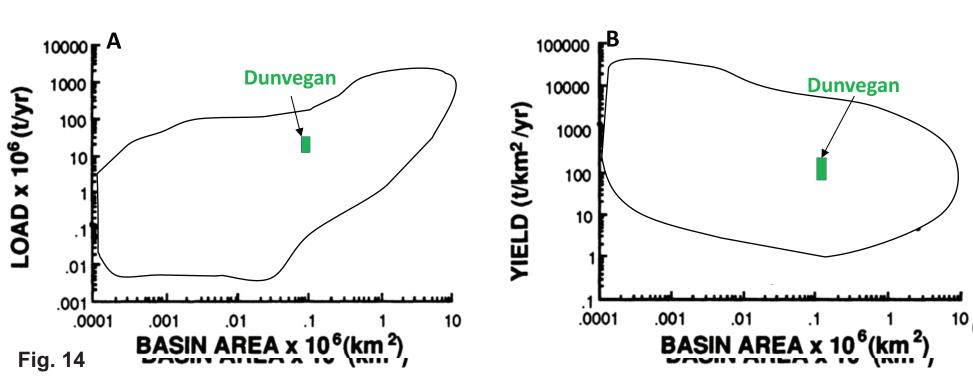


Figure 14. A. Sediment load vs. basin area; B. Sediment yield vs. basin area of the global river database. Note the strongly normal trend between sediment load and basin area, whereas the generally inverse relationship between yield and basin area (modified Milliman and Syvitski, 1992).

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 7.6×10^6 m³/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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