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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Summary

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 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 Alloformation 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 serve as a cross check of independent methods. Estimates of annual flood frequency and paleodischarge, associated with long-term geologic time estimates, are derived from chronostratigraphic analysis and allow calculation of cumulative sediment discharge. Isopach maps are used to measure sink-area sediment volumes. The results indicate that the trunk-river of Allomember E was 10 – 15 m deep and 150 – 250 m wide, carried fine- to medium-grained (< 200 microns) sand and flowed over a low-gradient paleoslope of $4.1 – 6.1 \times 10^{-5}$. Annual total sediment discharge is estimated to have ranged from 5.4 to 12×10^{6} m^3. Within 25,000 years, the river is estimated to have transported 135 – 307 km^3 of sediment into the basin. This is consistent with the 121 km^3 of sediment mapped in the study area. However, the upper range estimate of sediment delivered into the sink is three times the measured sediment volume in the map area, 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

Introduction

The source-to-sink (hereinafter referred to S2S) concept encompasses source sediment denudation from the initial catchment area, transportation or transient storage through the system, and ultimate deposition in the basinal sink (Bhattacharya et al., 2016; Romans and Graham, 2013; Sømme et al., 2011; Castelltort and Van Den Driessche, 2003; Leithold et al., 2015; Jaeger and Koppes, 2015). The S2S concept has been increasingly applied to assess sediment budgets of both modern and ancient systems (Sømme et al., 2009; Allen, 2008b; Carvajal and Steel. 2012; Sømme and Jackson, 2013). Given an ideally closed S2S system, the total sediment volume produced from the catchment should match the volume accumulated in downstream sinks (Holbrook and Wanas, 2014; Sadler and Jerolmack, 2015; Covault et al., 2011; Matenco et al., 2013; Paola and Martin, 2012; Paola, 2000; Petter et al., 2013; Sømme et al., 2011; Strong et al., 2005; Allen et al., 2013; Hajek and Wolinsky, 2012; Michael et al., 2013).

Theory and/or Method

In estimating total mass balance, it is assumed that the total sediment volume passing through any cross section of a longitudinal trunk fluvial system in the transfer zone during a certain time interval should match both the sediment volume delivered from the source area and the sediment volume passing through that cross section. This point in a cross section in the sediment routing system serves as a “fulcrum” that can be used to balance the total mass between source and sink (Holbrook and Wanas, 2014).

Examples

The purpose of this paper is to estimate total mass balance by calculating long-term sediment flux through fulcrum analysis of trunk-river deposits, with mapped downstream sediment accumulations in the Upper Cretaceous Dunvegan Alloformation, in the Alberta Foreland Basin, Canada, using a combination of outcrop and subsurface data. The Dunvegan Formation has been extensively studied, incorporating extensive outcrop and subsurface data to develop a high-resolution allostratigraphic and chronostratigraphic framework (Bhattacharya and Walker, 1991a, 1991b; Bhattacharya, 1992; Bhattacharya, 1993; Plint et al., 2001; Plint and Wadsworth, 2006; Plint, 2002; Plint et al., 2009; Plint, 2000; Plint and Wadsworth, 2003; Plint and Kreitner, 2007; McCarthy et al., 1999; Gingras et al., 1998; McCarthy and Plint, 2003). The Dunvegan is an ideal candidate for fulcrum analysis owing to the ability to identify and characterize the trunk-rivers within a specific incised-valley system and correlate these to the downdip lowstand deltaic and offshore shelf systems tracts (Plint and Wadsworth, 2006; Plint, 2002; Bhattacharya and Walker, 1991a) (Fig.1).

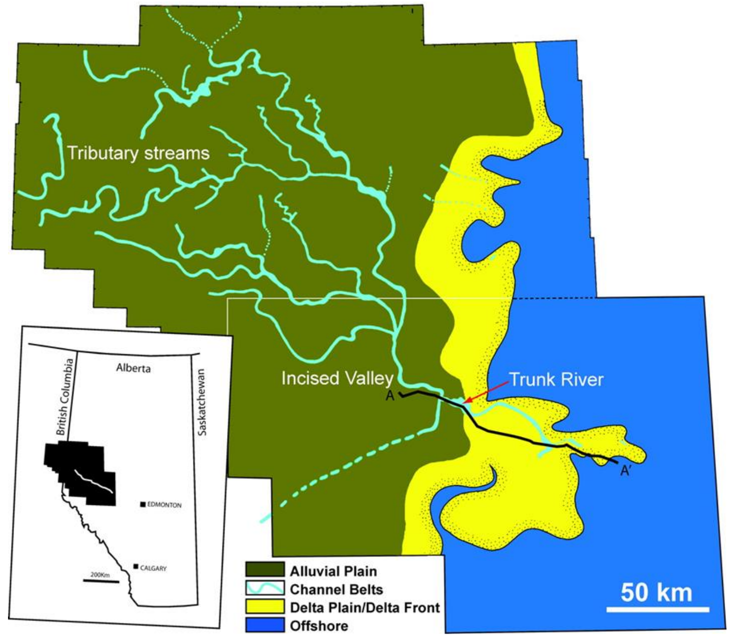

Figure 1. Paleogeographic map of valleys and lowstand deltas in Allomember E of the Dunvegan Formation (modifed after Bhattacharya and MacEachern, 2009).

Conclusions

The fulcrum approach assumes that the total mass balance in a closed S2S system should match the sediment volume delivered from the source area through a fulcrum point (i.e., trunk-river) to that deposited in the sink. Ancient trunk-rivers are prominent fulcrum candidates, paleohydrologic parameters of which can be used to estimate paleodischarge and instantaneous sediment volumes passing through them. Consequently, the total sediment volumes can be estimated with a deep-time depositional duration. The workflow comprises trunk-river dimension and paleoslope reconstruction, grain-size evaluation, instantaneous and annual discharge estimates, analysis of long-term depositional duration, and measurements of sink-area sediment accumulation.

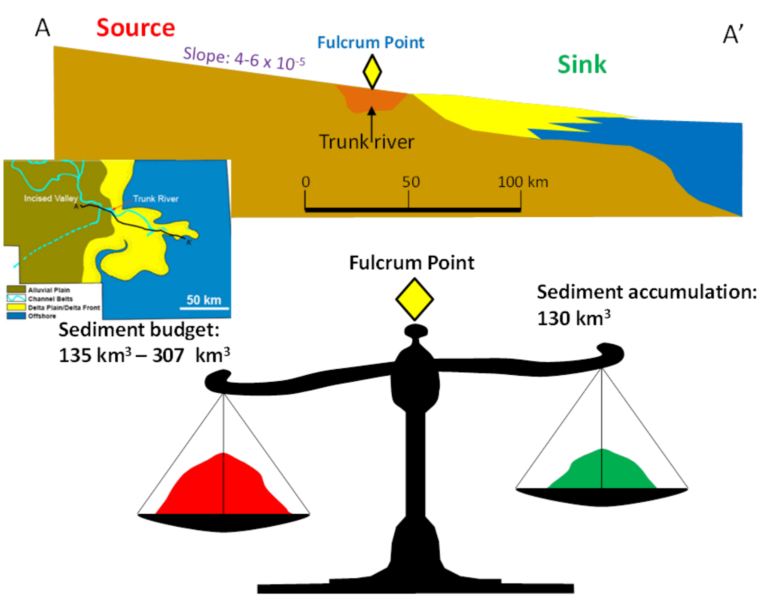

Figure 2. Cross section of the S2S system and mass balance diagram. A-A’ profile is sketched cross sectional view of trunk river longitudinal profile of Parasequence E1 in Allomember E, referred to inset map of Parasequence E1 paleogeography.

The fulcrum approach was tested in the Upper Cretaceous Dunvegan Alloformation by comparing the total mass balance between source sediment production and sink accumulation through paleohydrologic assessment of the trunk-river. The results indicate that the trunk-river of Allomember E was 10-15 m deep and 150-230 m wide, flowed over a low-gradient paleoslope of about 4.1 - 6.1 × 10^{-5}, and carried fine- to medium-grained sand. The river is estimated to have transported 1.4 × 10^{11} m^3 – 3.1 × 10^{11} m^3 (135-307 km^3) of sediment into the basin within 25,000 years, which is consistent with the 1.3 × 10^{11} m^3 (130 km^3) of sediment documented in the sink area. The upper-range estimate of sediment delivered to the sink is 2.5 times the measured sediment sink volume and suggest sediment escape on the shelf or sediment sequestration inland. This supports the hypothesis of mud dispersal in Dunvegan time and accommodation increase landward due to tectonic subsidence. The concomitant storm-initiated hyperpycnal flows could also help to explain the mud dispersal. These estimates also allow more robust comparison of ancient and modern analogs and their scaling relationships (Fig. 2).

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