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Invited review

Estimation of source area, river paleo-discharge, paleoslope, and sediment budgets of linked deep-time depositional systems and implications for hydrocarbon potential

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ABSTRACT

The source-to-sink (S2S) concept is focused on quantification of the various components of siliciclastic sedimentary systems from initial source sediment production areas, through the dispersal system, to deposition within a number of potential ultimate sedimentary sinks, and has more recently been applied to deep-time stratigraphic systems. Sequence-stratigraphic analysis is a key first step that allows depositional systems to be correlated and mapped, within a time-stratigraphic framework, such that fluvial transport systems can be linked to down-dip shorelines, shelf and deep-water deposits and interpreted in the context of allogenic processes. More recently, attempts have been made to quantify catchment areas for ancient depositional systems, using scaling relationships of modern systems. This also helps predict the size of linked depositional systems, such as rivers, deltas and submarine fans, along the S2S tract.

The maximum size of any given depositional system, such as a river, delta, or submarine fan, is significantly controlled by the area, relief, and climate regime of the source area, which in turn may link to the plate tectonic and paleogeographic setting. Classic provenance studies, and more recent use of detrital geochronology, including zircons, provide critical information about source areas, and place limits on catchment area. Provenance studies, especially when linked to thermochronometry also provide key information about rates of exhumation of source areas and the link to the tectonic setting.

In this paper the techniques for estimation of water and sediment paleodischarge and paleo-drainage area are outlined, and sediment budgets are calculated for a number of Mesozoic systems, primarily from western North America. The relevance for hydrocarbon exploration and production is discussed for each example.

In Mesozoic Western Interior basins of North America, extensive outcrop and subsurface data allow the largest trunk rivers to be identified, typically within incised valleys. Thickness, grain size, and sedimentary structures can be used to infer slope and flow velocities, and using width estimations, water and sediment paleodischarge can be calculated. River paleoslope can also be independently measured from stratigraphic-geometric considerations and used to assess paleo-river flow. Paleodischarge in turn is used to estimate the size of the catchment source area. Paleodischarge of rivers can also be estimated independently by integrating estimates of catchment source area, for example by using detrital zircons integrated with paleoclimate.

The catchment areas of North America evolved significantly during the late Mesozoic. During the Jurassic–Early Cretaceous, fluvial systems consisted of continental-scale low slope ($S = 10^{-4}$), axially drained rivers, forming the 40-m-deep channels in the Mannville Group in Canada, which now host the supergiant heavy-oil-sands reserves. During the times of maximum transgression of the Cretaceous Seaway, such as the Turonian and Campanian, the western North American foreland basin was characterized by smaller-scale (typically 10-m deep), steeper gradient ($S = 10^{-3}$) sand and gravel bedload rivers, dominated by transverse drainages in the rising Cordillera. This created a number of smaller river-delta S2S systems along the coast. As the Laramide Orogeny progressed, the Western Interior Seaway receded, and by the Paleocene the modern continental-scale drainage of North America was largely established with a major continental division separating south-flowing Mississippi drainages from north-flowing systems.

The integration of paleodischarge estimates with provenance analysis enables the improved use of the sedimentary record to make estimates about the entire S2S system, as opposed to primarily the depositional component.

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Clinothem stacking relationships and isopach mapping of stratigraphic volumes have also been integrated with chronostratigraphic data to analyze long-term S2S sediment budgets. A more quantitative approach to estimating the scale of erosional, transport and depositional components of sedimentary systems, especially in the context of linked source and depositional areas, also puts constraints on the size and scale of potential hydrocarbon reservoirs and thus has significant economic value.

Contents

1. Introduction: S2S in deep-time systems

The source-to-sink (S2S) concept focuses on quantification of the various components of sedimentary systems from source areas, through dispersal systems, and thence to deposition in a number of potential sedimentary sinks (Fig. 1). Boundaries of particular interest include the gravel–sand transition in the alluvial realm, the shoreline, the shelf-slope break, and the continental slope to deep-water transition. The NSF-funded S2S program focused on a 10-year analysis of a pair of high-gradient modern systems (Keuhl et al., 2015), the Fly-Strickland River and offshore systems of Papua New Guinea, and the Waipaoa River S2S system in New Zealand (e.g., Driscoll and Nittrouer, 2000; Aalto et al., 2008; Francis et al., 2008; Jorry et al., 2008; Slingerland et al., 2008; Carter et al., 2010; Marsaglia et al., 2010; Kuehl et al., 2015). The S2S results invited a closer look at ancient sedimentary systems and, in particular, how quantitative analysis of a given part of the stratigraphic archive can be used to make inferences or predictions about upstream control, or downstream limits of strata. Such predictions are of keen interest to the hydrocarbon industry, especially in the prediction of coarser-grained reservoir sediment volumes and quality, prediction of deep-water reservoirs, and estimations of mud-prone hydrocarbon source-rocks and sealing facies (now also unconventional reservoirs), which are key stratigraphic components of all petroleum systems (Magoon and Dow, 1994). A key technique in characterizing and modeling subsurface hydrocarbon reservoirs is the use of both modern and outcrop analogs to constrain the size, shape, and complexity of sedimentary bodies (e.g., Reynolds, 1999; Bridge and Tye, 2000; Bhattacharya and Tye, 2004; Tye, 2004; Pranter et al., 2009; Deveugle et al., 2014). Picking a correctly scaled analog can be critical in reservoir prediction, and can be greatly informed by S2S concepts that help define the nature of linked up-dip to down-dip depositional systems as a function of the catchment parameters (Bhattacharya and Tye, 2004).

The focus of this paper is to review how S2S concepts are applied to quantitative analysis of deep-time strata, with an emphasis on paleodischarge and sediment budgets, to determine the scaling relationships among the various components of the S2S system. The paper also provides examples of how S2S concepts can be applied to petroleum systems, especially in predicting sediment volumes, sandstone–shale ratios, and heterogeneity of conventional and unconventional reservoirs. Insights about sediment source areas, and especially climate and tectonics, provide predictions about reservoir quality, which is largely a function of sediment composition. The scale of a depositional system is ultimately limited by factors such as catchment area, climate, and relief, which in turn control river discharge (Syvitski and Milliman,