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Sediment Routing Systems: First Concepts

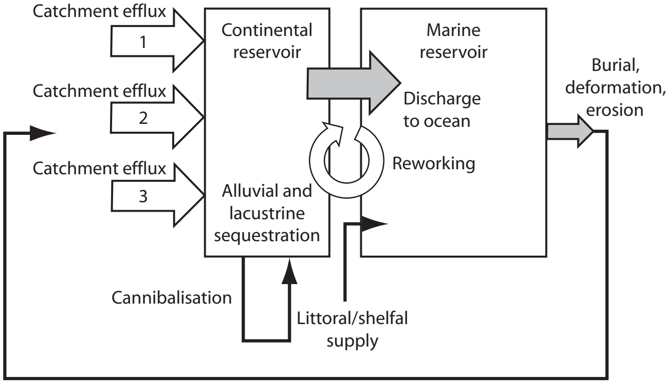
1.1 How Sediment Routing Systems Function

Sediment routing systems link the fate of particulate sediment from source to sink, and essentially frame the problems of denudation, sediment transport and deposition as a box model characterised by sources, reservoirs and sinks with connecting fluxes (Figure 1.1). Sediment routing systems, or denudation-accumulation systems (Einsele, Ratschbacher, and Wetzel, 1996; Hinderer and Einsele, 2001), are integrated, dynamical systems connecting regions of erosion, sediment transfer, temporary storage and long-term deposition (Meade, 1972, 1982; Schumm, 1977; Castelltort and Van Den Driessche, 2003; Allen and Allen, 2013; Romans and Graham, 2013; Sadler and Jerolmack, 2015). They involve a sediment cascade (Burt and Allison, 2010) from single or multiple source regions to long-term depositional sinks via a series of geomorphic environments characterised by intermittent storage (Section 1.2). The sediment routing system philosophy therefore firmly places geomorphology, sedimentology and stratigraphy within an Earth system context, but also forms the framework for allied investigations of, for example, global biogeochemical cycles.

Sediment routing systems represent a vigorous way in which the Earth recycles mass, and their dynamics are fundamental to global responses to, for example, supercontinental assembly and dispersal, mountain building and climate change (Whipple, 2009). They also provide thoroughfares for the transmission of chemical signals from mountains to the ocean (Meybeck, 1987; Hay, 1998; Galy et al., 2007). Sediment routing systems therefore participate strongly in many geochemical cycles, such as that of carbon (Leithold, Blair, and Wegmann, 2015), including in the drawdown of atmospheric CO_2 mediated by rates of chemical weathering (Raymo and Ruddiman, 1992), in the delivery of particulate organic carbon to the ocean and its removal from the short-term carbon cycle by rapid burial in deltas and sediment fans (France-Lanord and Derry, 1997; Galy et al., 2007), in the charging of coastal waters with nutrients (Orive, Elliott, and de Jong, 2002) and in the catalysing of ocean anoxia in sheltered and semi-enclosed seas by changes in freshwater discharge of rivers (Beckmann et al., 2005).

The concept of sediment routing systems was not until recently part of mainstream geological thinking, despite the fact that sediment provenance, based on sediment mineralogy (Boswell, 1933; Pettijohn, Potter, and Siever, 1987), bulk composition (Dickinson and

(a) Box model



(b) Network

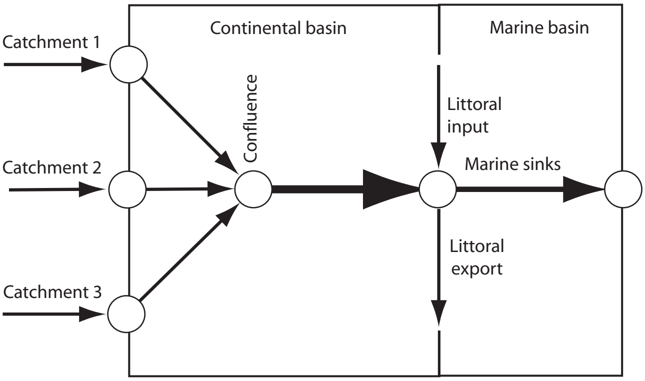


Figure 1.1 (a) Representation of a sediment routing system as a box model involving 3 sources and continental and marine sediment reservoirs. As sediment passes through the continental reservoir en route to the ocean, some of it is sequestered as alluvial and lacustrine sediment. Sequestered sediment may be cannibalised and enter the transport system again, and continental and marine reservoirs may be reworked as a result of base-level change. (b) The same sediment routing system as a network, showing schematic transport pathways. Discharge from the continent to the ocean is added to and subtracted from by marine sediment fluxes such as littoral transport.

Suczek, 1979) and palaeocurrents (Potter and Pettijohn, 1977), has been studied systematically for many years. The linkage between source and sink can be made by forward modelling the cascade of sediment (Section 1.2) from erosional landscapes primarily in terms of volumes and fluxes, but also in terms of sediment composition and grain size (Johnsson, 1993; Weltje and von Eynatten, 2004), and inversely by reconstructing source area characteristics from detrital mineralogy, thermochronology and geochronology.

Sediment dynamics in sediment routing systems is rarely smooth, continuous and uninterrupted like a relentless conveyor belt. Instead, the release of particulate sediment and dissolved solids from erosional source regions is neither uniform nor steady. These effluxes tend to be transient in relation to the forcing mechanisms. Some systems may respond quickly and linearly to a perturbation, in which case they can be termed ‘reactive’ (Allen, 2008a). Other systems may be sluggish to respond, and the signal may be transformed markedly during down-system propagation. Large alluvial systems have the ability to buffer incoming signals, which smooths out their amplitude and wavelength (Castelltort and Van Den Driessche, 2003; Allen, 2008a; Romans et al., 2015). The passage of signals through sediment routing systems therefore depends on the internal dynamics of sediment routing system segments and the ‘transfer zones’, ‘transition zones’ or ‘energy fences’ between them (Carvajal and Steel, 2009), some signals being effectively lost, or ‘shredded’, during transmission (Jerolmack and Paola, 2010). Sediment dynamics and hydrodynamics commonly change markedly at these transition zones, as takes place for example between river systems and the shoreface.

It is the passage of signals through the sediment routing system that causes different parts to be ‘teleconnected’. Most commonly, signals are communicated down-system, so that, for instance, a climate change in an erosional source region passes down to the ocean in the form of a change in particulate sediment discharge. Alternatively, a base-level change at a river mouth, for example caused by global sea level fall, passes up-system as an erosional wave that generates enhanced erosion rates in the source region. In this way, the entire sediment routing system is dynamically connected.

Buffering of signals is caused by the interruption of sediment transport by periods of intermittent storage (Malmon, Dunne, and Reneau, 2003; Allen, 2008b), which causes an increase in transit time for a grain-size population. As Philip Allen 2008a (p.274) put it:

> One can imagine tracking the trajectory of a single grain of sand from its source in mountain headwaters to its sink in a river flood plain, delta or the deep sea. Each grain would have a different trajectory and a different time in transit. The integration of a multiplicity of such trajectories defines a sediment-routing system, and an integration of the different transit times, were it possible, would provide information on the ability of the routing system to buffer incoming sediment flux signals.

The release of sediment from source regions carries a fingerprint that is potentially recognisable in basin stratigraphy in terms of mass fluxes, grain-size characteristics and sediment composition (Ibbeken and Schleyer, 1991, 2003). In a simple catchment-fan system, for example, where there is a single bedrock lithology such as granite, there will be little temporal change in sediment composition but a lateral compositional gradient caused by the hydraulic sorting of the different mineral components of the source region lithology. In such a case, particular diagnostic minerals, or index minerals, used in thermochronometric and cosmogenic dating, can be unambiguously connected to their hinterland source. Most basin-fills, however, are derived from multiple sources (Vezzoli, Garzanti, and Monguzzi, 2004; Weltje and Brommer, 2011) consisting of a range of bedrock lithologies, which induces a lateral (spatial) and vertical (temporal) variation in sediment composition in basin stratigraphy. The heterogeneous distribution of lithologies in the hinterland combined with the complexities of unroofing history produce a mixing structure in basin stratigraphy that is challenging to decipher. Specifically, the clast compositions of proximal conglomerates have been used to monitor the progressive erosion of source regions in tectonically active hinterlands (Graham et al., 1986; DeCelles, 1988). Complex mixing structures in basin stratigraphy make it more difficult to relate diagnostic minerals to their source region.

If stratigraphic units in the basin can be linked to source area lithologies, then the relative contribution of different source terrains can be assessed and sediment budgets estimated for the time span of interest. However, basin sediments may be recycled from older stratigraphy, chemical sediments must be accounted for, basin stratigraphy must be corrected to porosity-free solid volumes, and catchments serving as source areas for sediments must be correctly identified and delineated. Present-day sediment routing systems commonly benefit from the presence of well-defined and quantitatively characterised catchment areas but may suffer from a poor database on stratigraphy buried beneath the basin surface. Ancient sediment routing systems may have a well-known stratigraphy but source area parameters may be unknown or speculative. In some cases, the history of drainage evolution and sediment supply to adjacent basins can be evaluated on a continental scale (Simoes, Braun, and Bonnet, 2010). For example, the changing total sediment input to the Gulf of Mexico Basin over the Cenozoic (since 65 Ma) has been calculated from the supply from 8 fluvial axes draining a high proportion of the North American continental surface (Galloway, Whiteaker, and Ganey-Curry, 2011) (Figure 1.2). Peaks in sediment delivery, evaluated from depositional volumes, of 150×10^3 km^3 Myr^{-1} occurred in the Palaeocene and Pleistocene. The Mississippi River delivers the bulk of the sediment entering the Gulf of Mexico at the present day. The modern TDS (total dissolved solids) of 400 Mt yr^{-1}, equivalent to 150 km^3 Myr^{-1}, is in agreement with the long-term value derived from the volumes of depositional episodes in the Gulf of Mexico Basin. In well-constrained examples, sediment volumes may be inverted to obtain mean catchment erosion rates over geological timescales that can be compared with estimates derived from thermochronometric methods (Rouby et al., 2009; Carvajal and Steel, 2012; Michael et al., 2014b).

A major goal within the broader remit of sediment routing systems research is to gain predictive capability of subsurface compositional and granulometric trends. Harnessing such capability would be highly beneficial to the understanding of the flow of fluids through the porous media represented by basin sediments, with applications to hydrocarbon production, contaminant fluxes in groundwater and drawdown of aquifers as well as to basin analysis. Yet it is problematical to sample subsurface stratigraphy at the resolution required to build a reliable database. To make progress demands more than an inversion of field observations. A holistic analytical approach was proposed by Heins and Kairo (2007) in which all of the factors controlling sand composition and texture were analysed together, chief of which are tectonics, geomorphology, lithological make-up of the source region, weathering and transport processes. These factors are constrained by quantitative input on source region lithologies, the regional topographic gradient, climate (weathering and transport potential), transport distance in the source catchment and in the depositional basin, basin subsidence rate and depositional facies (Heins and Kairo, 2007).

The total volume of sediment deposited in the sediment routing system and the spatial extent of its footprint, or ‘fairway’ (Michael, Whittaker, and Allen, 2013; Michael et al.,

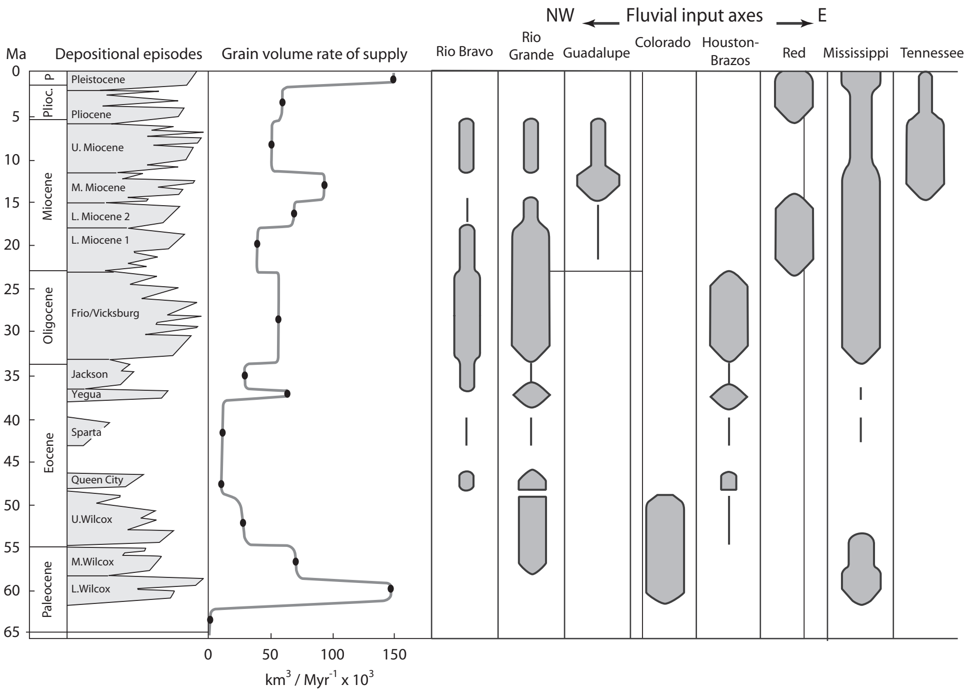


Figure 1.2 Chronology of Cenozoic depositional episodes in the Gulf of Mexico Basin, total (porosity free) sediment supply (in km^3 Myr^{-1} × 10^3) as a function of time, and the individual contributions from 8 fluvial axes calculated from volumes of depositional episodes. Width of bar indicates volumetric importance of supply to depocentre. Modified from Galloway, Whiteaker, and Ganey-Curry (2011) (fig.1, p.940; fig.3, p.943), with permission of Geological Society of America.

2014a), provides the basis for a sediment budget. Sediment budgets allow a connection to be made between hinterland erosion and basin filling, and also potentially explain the downstream evolution of sedimentary facies, stratigraphic architectures and the partitioning of grain size (Cross and Lessinger, 1998; Granjeon and Joseph, 1999) (Figure 1.3). Sediment is fractionated by particle size during transport (Cross and Lessinger, 1998), principally by selective extraction from surface fluxes to build stratigraphy (Strong et al., 2005; Allen, 2008a; Paola and Martin, 2012; Michael et al., 2013), producing a down-system trend in the relative proportions of grain-size classes and in the mean grain size of gravel and sand (Fedele and Paola, 2007; Duller et al., 2010; Whittaker et al., 2011; Parsons et al., 2012; Michael et al., 2013).

Laboratory experiments (Toro-Escobar, Parker, and Paola, 1996; Sheets, Hickson, and Paola, 2002; Strong et al., 2005; Paola et al., 2009; Paola and Martin, 2012; Rohais, Bonnet, and Eschard, 2012), numerical models (Allen and Densmore, 2000; Densmore, Allen, and Simpson, 2007a; Duller et al., 2010; Jerolmack and Brzinski, 2010; Armitage et al., 2011) and field studies (Duller et al., 2010; Whittaker et al., 2011; Carvajal and Steel, 2012; Parsons et al., 2012) have concluded that the main controls on stratigraphic architectural

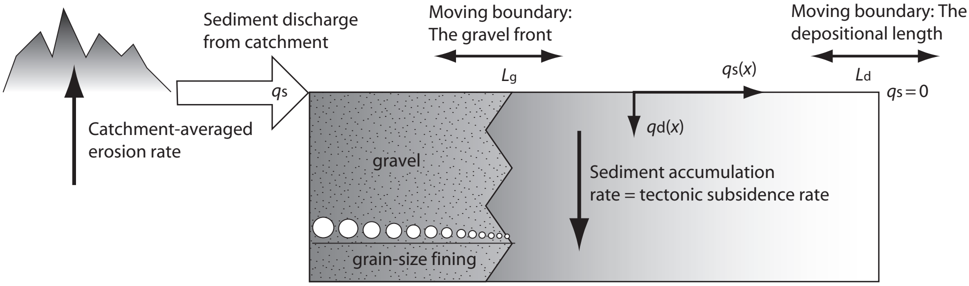


Figure 1.3 Sediment dispersal and deposition in a sediment routing system. Sediment is discharged from a source region q_s into a basin undergoing subsidence. Sediment is selectively extracted from the surface flux $q_s(x)$ to build stratigraphy $q_d(x)$, causing a down-system fining of mean grain size. The dynamics of sediment dispersal and deposition are reflected in the migration of moving boundaries such as the gravel front (Section 8.1.1). From Allen and Allen (2013) (fig.7.49, p.274) with permission of John Wiley & Sons, Inc.

trends in continental basins are: (1) the sediment supply to the basin, which Allen et al. (2013) referred to as the 'Qs problem', (2) the characteristic grain-size mix of this sediment (Allen et al., 2015b), (3) the spatial distribution of subsidence and base-level changes controlling accommodation and (4) hydraulic parameters and sedimentary processes in the basin. One of the most important aspects underpinning the sediment routing system concept and aiding downstream stratigraphic prediction is therefore the volumetric or mass sediment budget.

Sediment budgets, despite their generic value in illustrating how the sediment routing system functions, are unique to the case being studied (Hinderer, 2012). This problem can be overcome by setting the surface sediment discharges and depositional fluxes of sediment routing systems within a mass balance framework (Strong et al., 2005; Paola and Martin, 2012; Michael et al., 2013). In the mass balance framework, the cumulative deposited volume of sediment in the down-system direction is normalised by the total sediment volume and the total depositional length (Figure 1.4), and thereby illustrates in a dimensionless fashion the interplay between the depositional flux and the bypassed surface sediment discharge. This not only allows systems of different shapes and lengths, but also of different total sediment volumes, to be compared, and potentially permits the upscaling of small laboratory tests to real stratigraphic problems (Strong et al., 2005; Paola and Martin, 2012).

A mass or volume balance of the entire system allows a sediment budget to be evaluated that balances the particulate sediment derived by physical weathering against sediment volumes in depositional sinks (Clift et al., 2001a; Slaymaker, 2003; Tinker, de Wit, and Brown, 2008; Carvajal and Steel, 2012; Hinderer, 2012; Michael et al., 2014b). Quantification of the sediment budget, its component fluxes and the down-system evolution of grain size therefore provides essential information to calibrate and test predictive models of basin filling and sedimentary architecture (Paola, Heller, and Angevine, 1992; Marr et al., 2000; Armitage et al., 2011; Kim et al., 2011), including those derived from sequence stratigraphy.

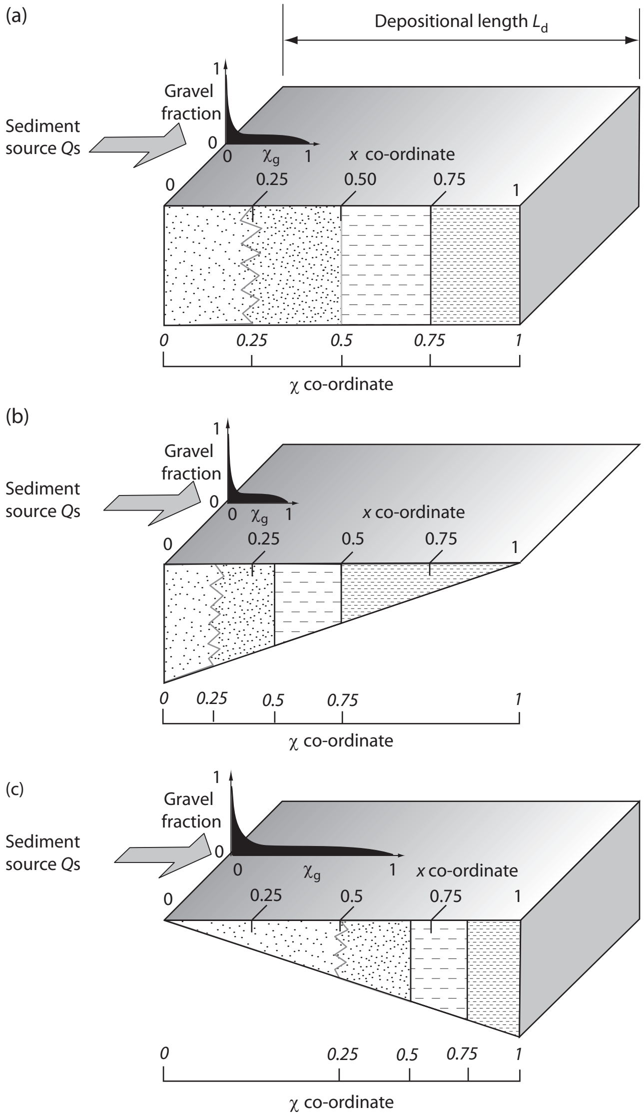


Figure 1.4 The transformation from Cartesian co-ordinates into a mass balance framework for different basin cross-sectional shapes. The down-system co-ordinate x is transformed by normalising the depositional volume (or mass) by the total volume (or mass) deposited in the entire sediment routing system. The mass balance co-ordinate χ therefore varies between 0 (at the origin, or apex of the depositional system) to 1 at the depositional length L_d where sediment is exhausted. This allows sediment routing systems with different sediment budgets, accommodation and size to be directly compared. Modified from Michael et al. (2013) (fig.4) with permission of University of Chicago Press.

Strong et al. (2005) and Paola and Martin (2012) showed from both laboratory and subsurface studies that fluvial and deep marine sedimentary architectures and grain-size patterns are governed primarily by mass extraction by selective deposition over geological timescales. In other words, for the same ratio of sediment supply to total accommodation space in any basin, the same facies assemblages and the same bulk grain-size characteristics are expected to be present, regardless of system length and spatial pattern of tectonic subsidence. Consequently, extraction of certain grain sizes by selective deposition provides a fundamental control on the availability of finer grain sizes downstream, thereby controlling depositional environments, facies and stratigraphic architectures.

Sediment routing systems might be categorised and named from their source, their main artery of sediment transport or their main depocentre. There are difficulties in whichever method of categorisation in chosen. Most natural sediment routing systems have multiple sediment sources, more than a single sediment transport system and occasionally different depocentres (multi-source and multi-sink systems). For example, the western Adriatic mud wedge is fed by the Adige, Po and several Apennines rivers (Weltje and Brommer, 2011). Coastal currents supply the macrotidal Gulf of Kachchh in western India with sediment derived from both the perennial Indus River as well as from a number of small ephemeral ‘dryland’ streams (Prizomwala, Bhatt, and Basavaiah, 2014). The Golo sediment routing system of the western Mediterranean is fed from a single catchment in Corsica, but its efflux is joined by the contribution of a littoral cell; sediment is stored on the continental shelf and slope and intermittently discharged through shelf-edge canyons to lobes on the deep sea floor of the Corsican Trough (Sømme et al., 2011). At a larger scale, the Orange River drainage basin supplies sediment to a number of passive margin basins stretching from the Falkland-Agulhas fracture zone in the south to the Walvis Ridge in the north (Rouby et al., 2009). A number of independent fluvial systems draining the North American continent, such as the Brazos, Colorado and Mississippi, have supplied large volumes of sediment to the Gulf of Mexico during the Cenozoic (Galloway, Whiteaker, and Ganey-Curry, 2011). Each river system has its own coastal delta at times of sea level highstand, but river systems merge on the continental shelf at times of sea level lowstand (Blum and Aslan, 2006; Blum and Garvin, 2010) (Figure 10.9). The deep marine fan of the Bay of Bengal is supplied with sediment from multiple sources, including the rivers of the eastern Ghats of peninsular India and the Ganges, Brahmaputra, Salween and Irrawaddy river systems draining the Himalaya-Tibetan region. The networks of sediment routing systems, as shown generically in Figure 1.1, may therefore be complex (Figure 1.5). In many cases, the sediment routing system can be named according to its main river artery. These main arteries correspond closely to those rivers with outlets into oceans, inland seas and lakes, so the categorisation of sediment routing systems is essentially the same as the challenge facing the authors of global databases of sediment delivery to the ocean (Milliman and Farnsworth, 2011). This option of naming sediment routing systems from their main river arteries was adopted by Helland-Hansen et al. (2016) in their review of ‘Earth’s natural hourglasses’.

Sediment routing systems are termed ‘Earth’s natural hourglasses’ (Helland-Hansen et al., 2016) since they commonly involve a fairway that is broad in the hinterland

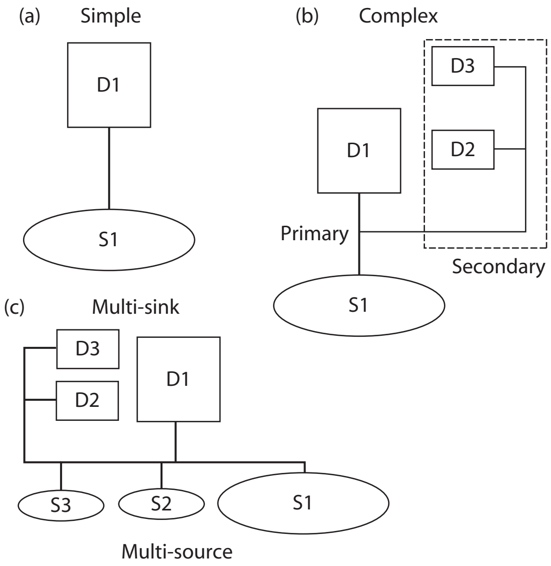


Figure 1.5 Sediment routing system networks, which may be (a) simple or (b) complex, with primary or secondary pathways, and comprise (c) multiple sources and sinks. S, Source; D, Depositional sink.

catchment and broad in the depositional zone, but relatively narrow in the transitional zone between. Source-to-sink systems are viewed in a framework with three end-member types: (1) ‘steep, short and deep’, which occur along active plate boundaries, and are ‘reactive’ (Allen, 2008a), such as the Var and Golo of the Mediterranean Sea and Monterey and Astoria of the California Borderland; (2) ‘wide and deep’, which are characteristic of passive continental margins, and are ‘buffered’, such as the Rhône, Danube, Niger, Zambezi, Congo, Mississippi, Amazon and Nile; and (3) ‘wide and shallow’, which are commonly located on normal thickness continental crust such as in foreland basins and cratonic basins, as in the Po and Ganges. Clearly, there is a strong tectonic control on the occurrence of this variability in sediment routing systems (Section 8.6).

The networks of sediment routing systems may thus be simple, involving a single source area linked unambiguously to a single depositional sink, or complex, with additional sources, sinks and sediment transport pathways (Figure 1.5). Complex sediment routing systems may involve a primary route for sediment dispersal and a secondary route carrying lower sediment discharges. Many sediment routing systems contain multiple sources and, less commonly, multiple sinks (Table 1.1).

1.2 The Sediment Cascade

Particulate sediment and dissolved solids cascade through the sediment routing system with characteristic fluxes, which allows it to be treated as an essentially closed system in terms of volume or mass (Figure 1.6). Closure of the sediment budget is a powerful tool, but

Table 1.1. *General attributes of sediment routing system networks.*

Attribute	Examples
Simple	Catchment-fan systems (Death Valley, Owens Valley)
	Eel River system, Oregon Shelf
	Var system and deep-water fan, Nice
Complex	Bengal Fan
Primary	Nile delta
	Rhône Fan
	Indus Fan
Secondary	Levant margin littoral cell
	Roussillon-Languedoc littoral current
	Eastern Ghats sources for Bengal Fan
Multi-sink	Amazon outflow
	Orange, southwest Africa
	Golo, Corsican Trough
Multi-source	Bengal Fan
	Tarim Basin
	Western Adriatic mud wedge
	Newport Fan, Santa Ana system
	Gulf of Mexico
	Gulf of Kachchh, Arabian Sea, India

there are a number of reasons why this is problematical. The main reason is that solute fluxes enter the ocean to join a globally mixed pool. In addition, marine depositional sinks may be difficult to identify, constrain and sample, and very fine-grained sediments may be transported far into the open ocean. Third, part of the sediment routing system budget may involve sediment transported by wind. Nevertheless, notwithstanding these problems, to describe a sediment routing system ideally requires the identification of regions of sediment generation, transport and deposition, together with the estimation of the fluxes of particulate sediment and solutes that connect them.

In a hypothetical unglaciated sediment routing system, sediment is released from hillslope regolith by soil creep, debris flows and landslides and is transferred to catchment channels. A new set of processes is involved in the evacuation of this stored sediment from the catchment into the fluvial system. Further processes are responsible for down-system advection, principally by floods, and intermittent storage in channel bars, levees, splays and floodplains. Subsequent floods may or may not entrain these deposits. The result is that sediment takes a large number of stochastic steps towards the coast. At the coast, new processes take over to transport sediment by waves, tides, jets, geostrophic flows and gravity flows to storage sites as shorelines, estuaries, coastal marshlands, deltas, shallow marine sand sheets, shelfal mud belts, and coastal and shelf-edge clinoforms and sediment prisms. In some cases, the ultimate sink is these coastal and shallow marine deposits, and

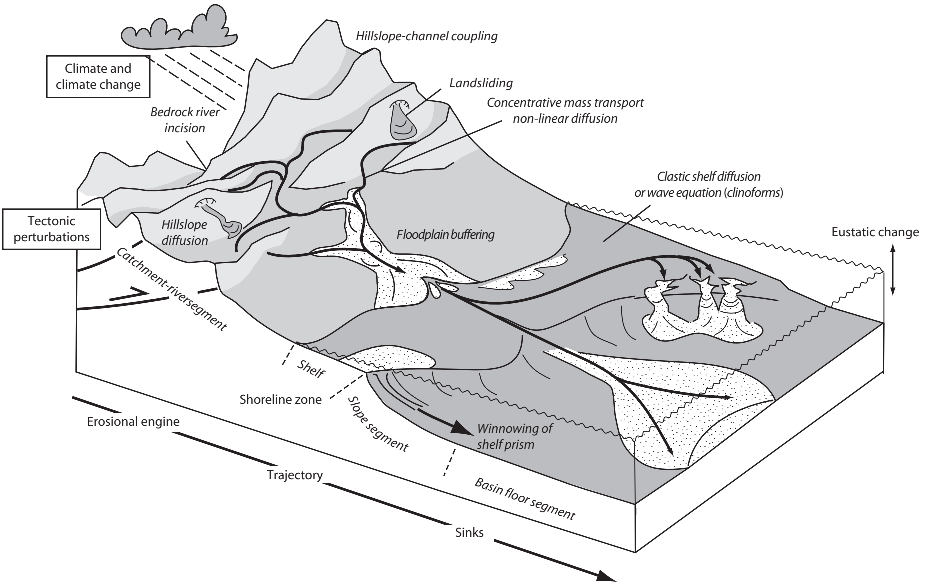


Figure 1.6 Concept of the sediment routing system from source to sink. The sediment routing system is driven and perturbed by tectonics and climate. It comprises a number of morphodynamic, mutually coupled subsystems or segments. The erosional engine feeds sediment to a predominantly transportational system (the trajectory) and to long-term sinks. From Allen and Heller (2012) (fig. 6.2, p.113), with permission of John Wiley & Sons, Inc.

no sediment escapes onto the continental shelf and into the deep sea, as in Chesapeake Bay, on the Atlantic coast of the United States (Meade, 1982). However, a final step may remobilise some of the riverine or marine sediment and transport it to depositional sinks on the continental slope and deep basin floor (Figure 1.6). When viewed at the medium to long timescale (more than 10^3 yr), sediment is simply released from upland sources and delivered to marine sinks. At the shorter timescale, however, more important sources and sinks are the storage sites along the sediment cascade, such as valley bottoms, terraces and floodplains. The delivery of sediment to the marine basin floor (Covault and Graham, 2010) is therefore the end of a series of stochastic steps from sites of storage, known as ‘transient states’ or ‘staging areas,’ to the ‘absorbing state’ (Malmon et al., 2005) of long-term deposition at the terminus of the sediment routing system (Figure 1.7). Sediment routing systems, or individual segments within them such as the continental shelf, may act as ‘conveyors’ or ‘capacitors’ in terms of the transmission of sediment (Covault and Fildani, 2014).

Consequently, although in some instances sediment pulses may pass rapidly through the routing system and in one cycle arrive on the deep marine basin floor, bypassing intervening transient states, it is more common for signals originating in the source region, such as the grain-size distribution of the sediment efflux, to be subject to transformation during propagation through the sediment routing system (Weltje, 2012; Romans et al., 2015).

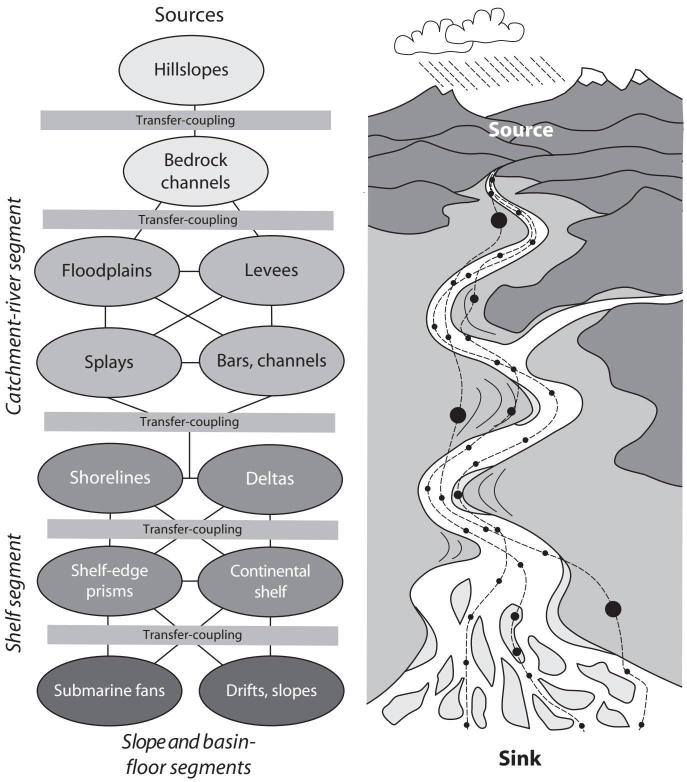


Figure 1.7 Right: sediment is transferred from a source region to a sink along trajectories (dashed lines). Some trajectories involve short transit times with brief periods of storage in the sediment routing system (small circles), whereas others involve long transit times with prolonged periods of storage in transient states (large circles). Long periods of storage of sediment in transient states implies buffering of sediment supply signals. Modified from Malmon, Dunne, and Reneau (2003) (fig.1, p.526). Left: sources, sites of temporary storage (transient states) and sites of permanent storage (absorbing states). The transfer of sediment between macrogeomorphic segments may be complex and involve dynamic feedbacks. From Allen and Heller (2012) (fig.6.1, p.112) with permission of John Wiley & Sons, Inc.

Within a sediment routing system undergoing tectonic subsidence, part of the surface flux in the sediment cascade is selectively sequestered at any point along the routing system, until the surface flux becomes exhausted at the downstream depositional limit (Paola and Voller, 2005; Fedele and Paola, 2007; Allen, 2008a; Paola et al., 2009; Duller et al., 2010; Allen and Heller, 2012; Paola and Martin, 2012; Michael et al., 2013, 2014a,b). Over geological time, depending on the available accommodation and position of base level (Muto and Steel, 2000), a portion of this depositional flux is locked into stratigraphy (Allen and Heller (2012), fig.6.3), a phenomenon sometimes broadly referred to as 'Landscapes into Rock' following the William Smith meeting with this name at the Geological Society of London in 2010 (see http://romania-rocks.blogspot.co.uk/2010/09/landscapes-into-rock-part-1.html). The sequestration of merely a portion of the surface flux of sediment to build stratigraphy, the intermittency and spatial limitations of depositional events and the obliterating effects of erosion together imply that the stratigraphic record is a far from complete recorder of time. Allen (2008a) (p.275) wrote:

> Time transforms sediment routing systems into geology, and like history, selectively samples from the events that actually happened to create a narrative of what is recorded.

The simplest sediment routing system that can be imagined comprises a single upland catchment that feeds sediment to a basin-margin fan, acting in a closed system, with no sediment escape (Humphrey and Heller, 1995; Allen and Hovius, 1998; Allen and Densmore, 2000; Carrétier and Lucazeau, 2005; Densmore, Allen, and Simpson, 2007a; Pépin, Carrétier, and Herail, 2010). In a prototype such as this, sediment can be unambiguously linked to lithological sources in the hinterland catchment, and thermochronological and cosmogenic signatures in the depositional sink of the fan can be reliably connected to erosion in the source (Stock, Ehlers, and Farley, 2006). Commonly, however, sediment routing systems are more complex and involve far-field sediment transport, well-developed alluvial sequestration (Castelltort and Van Den Driessche, 2003; Allen, 2008b; Covault et al., 2013), complex sediment transport dynamics in the coastal and continental shelf areas (Covault and Fildani, 2014) and multiple sources and/or multiple sinks (Vezzoli, Garzanti, and Monguzzi, 2004; Weltje and Brommer, 2011) (Table 1.1) (Figure 1.5).

Some sediment routing systems are continental in scale, involving sources in strongly contrasting climatic and tectonic settings, such as the Ganges and Brahmaputra systems draining into the Bay of Bengal (Einsele, Ratschbacher, and Wetzel, 1996; Clift et al., 2001a; Curray, Emmel, and Moore, 2002). In large, complex examples, sediment can be traced back to source regions using a range of provenance methods (analysis of pebble lithologies, heavy minerals, isotopic fingerprinting and geochronology of detrital grains) (Section 9.5), but mixing of fingerprints from different sources during sediment transport and down-system attenuation of source area signals introduce considerable uncertainties in linking source(s) to sink(s). Identification of source areas for detrital minerals in the basin is important in understanding where sediment ultimately comes from, but is only a part of understanding the sediment routing system. As Allen (2008a) (p.275) writes:

> No matter how we make this match between erosional source area and depositional sink, provenance studies cannot help us to fully understand the dynamics of the sediment routing system that conveyed [the sediment] from source to sink. It is rather like being present at the birth of a baby and the funeral of a man, but missing out on the life story.

Most studies of the sediment budget have addressed relatively modern systems, where catchments serving as source regions and depositional sinks, such as dams, natural lakes and floodplains, as well as the continental shelf, are well defined (Einsele and Hinderer, 1997; Hinderer, 2012). Most present-day sediment routing systems are strongly influenced by human activities. Longer-term budgets have also been estimated, particularly in the context of climate change and tectonic activity in mountain belts acting as source regions, commonly using sediment isopachs derived from seismic reflection data, borehole information and stratigraphic outcrops (Barnes and Heins, 2009; Brommer, Weltje, and Trincardi, 2009; Rouby et al., 2009; Lopez-Blanco et al., 2010; Weltje and Brommer, 2011; Carvajal and Steel, 2012), by palaeohydrological analysis of upstream fluxes from cross-sections of alluvial deposits (Holbrook and Wanas, 2014), from inventories of lake basin, valley and delta volumes (Kuhlemann et al., 2002; Walford, White, and Sydow, 2005; Tinker, de Wit, and Brown, 2008), and from geochemical indices (Galy and France-Lanord, 2001). A range of studies have addressed the long-term sediment delivery to the ocean from rivers at the basin scale using seismic reflection and borehole data in the depositional sink (Métivier and Gaudemer, 1999; Clift and Gaedicke, 2002; Walford, White, and Sydow, 2005; Tinker, de Wit, and Brown, 2008; Rouby et al., 2009; Galloway, Whiteaker, and Ganey-Curry, 2011; Guillocheau et al., 2012).

By connecting source to sink, and by keeping an inventory of the grain-size fractionation, depositional volumes and sediment calibre can be integrated throughout the sediment routing system fairway, which solves concurrently two challenging problems: (1) the total volume of particulate sediment derived from mountain catchments serving as 'erosional engines' averaged over geological timescales can be calculated (Carvajal and Steel, 2012) and compared with erosion estimates derived from thermochronology (Tinker, de Wit, and Brown, 2008; Rouby et al., 2009; Michael et al., 2014b), and (2) the 'global' size distribution of sediment released from mountain catchments at long timescales can be obtained (Michael et al., 2014a) and used as a boundary condition in models of sediment dispersal. For example, the 'global' grain-size mix fluxed out of mountain catchments to supply the mid-upper Eocene Escanilla palaeo-sediment routing system of the wedge-top zone of the southern Pyrenees was 9% gravel, 25% sand and 64% finer than sand, based on about 4,000 km^3 of sediment released over a 7.7 Myr period (Michael et al., 2013, 2014a).

Erosion and deposition rates, sediment fluxes and grain sizes can be calculated in modern sediment routing systems using a variety of techniques targeted at short-term observational periods, but these calculated values cannot be easily upscaled to the longer timescales of geological sediment routing systems. Ancient sediment routing systems, however, are difficult to recognise and investigate: they are likely to be only partially preserved as stratigraphy, making the definition of their fairway problematical; depositional sinks are commonly disconnected from erosional source regions; there may be multiple sources, some of which may be difficult to identify using conventional provenance methods; and the chronological resolution may be inadequate to allow a confident correlation scheme to be developed. Constraining the sediment budget of a geological sediment routing system is therefore a deceptively challenging task, but one that is vital if we are to couple measurements of rock exhumation and erosion rates in mountain belts with realistic estimates of the timing, locus and magnitude of sediment supply to basins (Sinclair et al., 2005; Beamud et al., 2010; Whitchurch et al., 2011; Carvajal and Steel, 2012; Filleaudeau, Mouthereau, and Pik, 2012; Parsons et al., 2012).

Beyond the river mouth, the continental shelf can either act as a capacitor (storage or staging area) or as a conveyor for sediment from the land to the deep sea (Covault and Fildani, 2014). Shelves are conventionally regarded as capacitors during periods of rising and high relative sea level (Vail, Mitchum, and Thompson, 1977; Jervey, 1988), when the shelf offers accommodation for sediment preservation, and low river gradients during times of elevated sea level result in lower fluxes of sediment delivered to the shelf. On the other hand, shelves may act as conveyors, particularly where canyons are incised into continental shelves and intersect nearshore sediment transport pathways, or where high sediment discharges from the land cause submarine deltas to migrate to the shelf edge.

Off-shelf transport to the deep sea is therefore affected by a number of factors:

1. Relative sea level: transport rates may be reduced at times of sea level highstand due to a reduction in river gradients (Posamentier and Vail, 1988; Burgess and Hovius, 1998; Covault and Graham, 2010).
2. Shelf width: off-shelf transport may reduce as shelf width increases, which increases shelf accommodation (Posamentier, Erskine, and Mitchum, 1991; Walsh and Nittrouer, 2003).
3. Sediment supply: transport to the deep sea may increase by the driving of deltas to the shelf edge by high sediment discharges (Burgess and Hovius, 1998; Covault et al., 2007; Carvajal, Steel, and Petter, 2009).
4. Connection of canyon heads: effective conveyance of the shelf is critically dependent on the connection of canyon heads to high river and littoral sediment discharges (Covault et al., 2011).

Although Eel Canyon, offshore California, is currently disconnected from large fluvial or littoral sediment sources, as it has been over the last thousands of years of rising and high sea level (Burger, Fulthorpe, and Austin, 2001), over the hundred year timescale, sediment budget studies indicate that a large percentage (approximately 80%) of sediment has been exported from the shelf into the deep sea (Sommerfield and Nittrouer, 1999). Covault and Fildani (2014) therefore point out that the Eel shelf acts as a conveyor over the short timescale of the last century while acting as a capacitor at the timescale of the last million years.

The Washington–Oregon shelf is wider (25–60 km) than the Californian shelf (average of 5 km) and is fed principally by the large sediment discharge of the Columbia River (5–10 Mt yr^{-1}), half of which is sequestered on the shelf (Sommerfield and Nittrouer, 1999). Maxima in the delivery of sediment from the Columbia River are out of phase with periods of high wave and current reworking, which promotes shelf storage. However, routing of sediment to the Astoria canyon and fan system was most efficient during periods of post-glacial marine transgression, when climate systems caused intense terrestrial flooding. The Washington–Oregon shelf therefore acts as a capacitor at the short timescale of the present day, but as a conveyor during periods of post-glacial climate instability at the timescale of glacial-interglacial cycles (Covault and Fildani, 2014).

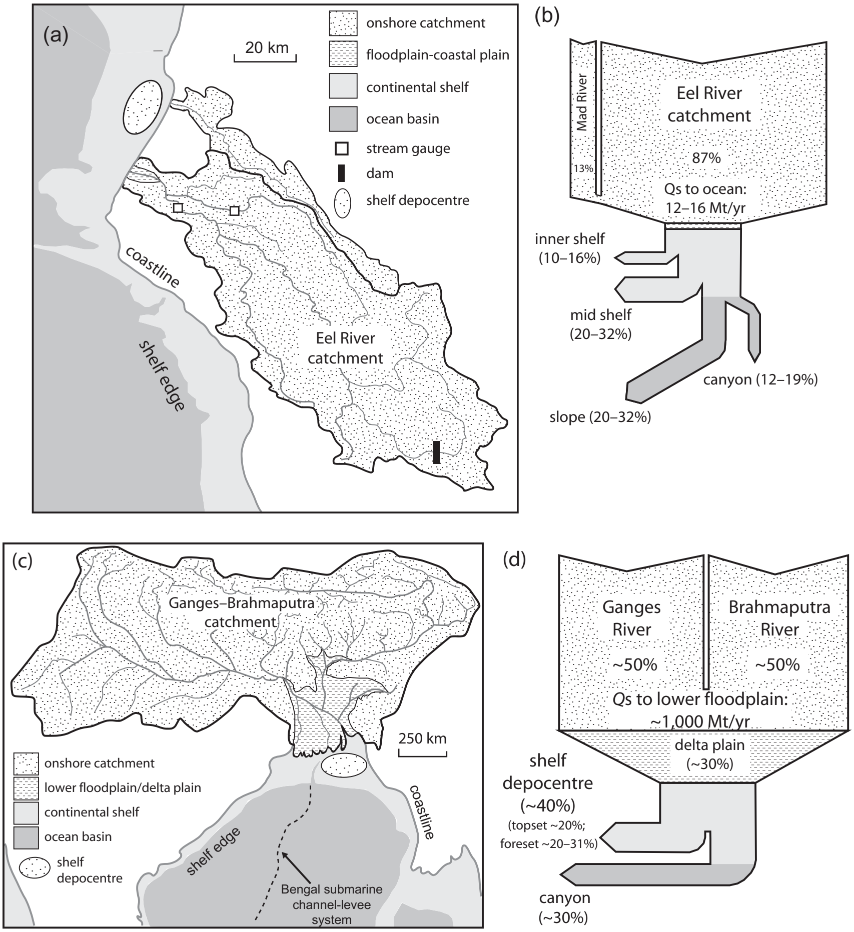


Figure 1.8 (a), (b) Combined Eel-Mad sediment routing system, northern California, showing upstream catchment area and storage areas in the coastal floodplain, shelf, continental slope and canyon leading to the deep sea. Sediment budget estimates are from Sommerfield and Nittrouer (1999) and Warrick (2014). (c), (d) Combined Ganges–Meghna–Brahmaputra sediment routing system showing upstream catchments and storage areas of the delta plain, shelf and Bengal submarine fan channel-levee system. Budget estimates are from Kuehl et al. (2005). Modified from Romans et al. (2015) (figs.3, 4) with permission of Elsevier.

The varied styles of routing of sediment in the cascade from source to sink can be illustrated from two examples (Figure 1.8). The previously mentioned Eel sediment routing system has a source region (area of 9,400 km^2) in the mountainous topography of northern California (Nittrouer et al., 2007) with a sediment discharge to the Pacific Ocean of 12–16 Mt per year. Sediment discharges, most importantly in major floods, construct a prism on the continental shelf, but most sediment is exported beyond the shelf edge to the deep sea (Wheatcroft and Borgeld, 2000). Export to deep water is enhanced by storm wave action superimposed on sediment gravity flows.

In contrast, the large Ganges–Brahmaputra system (catchment area 1,656,000 km^2) exports sediment to the vast Bengal Fan. At the historical timescale, about 30% of the sediment released from source areas is trapped onshore, principally in tectonically subsiding alluvial areas (Allison, 1998; Goodbred and Kuehl, 1999). Approximately 20% of the sediment delivery to the ocean builds topsets of subaqueous clinoforms, and 20–31% is stored in clinoform foresets, but along-shelf currents transport the remaining sediment to the head of a major canyon (Swatch of No Ground) and thereby to the Bengal submarine fan. Cyclones are particularly effective in advecting sediment to the canyon, and trigger mass transport events that travel down to the Bengal Fan.

A realistic assessment of the nature of the sediment cascade from source to sink in most real-world sediment routing systems clearly demands a sound understanding of the surface dynamics of sediment transport in a broad range of environmental settings. This is challenging enough, but to interpret the stratigraphic record, and to invert it in order to understand Earth history, requires us to also appreciate the 'long result of Time'. Until the geomorphic and oceanographic perspectives of the modern Earth and its land-ocean linkages (Romans and Graham, 2013) are more closely married with the geological perspective of deep time, we will find that we are like the fortune-teller in Shakespeare's *Antony and Cleopatra*, who says:

> In Nature's infinite book of secrecy, A little I can read.

The sediment routing system philosophy offers an avenue of making progress through such a marriage.