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Hierarchy of source-to-sink systems — Example from the Nile distribution across the eastern Mediterranean

Uri Schattner *, Michael Lazar

Dr. Mosses Strauss Department of Marine Geosciences, Charney School of Marine Sciences, University of Haifa, Israel

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ABSTRACT

A standard source-to-sink approach examines sediment transport along an imaginary axis (regarded here as primary) extending between land, the continental margin and a nearby basin. This approach oversimplifies the development of depositional environments located off the axis (regarded here as secondary). Similarly, it imposes that factors affecting the primary source (e.g. climate) will directly be reflected in the secondary sink. The current study examines this suggested hierarchy in a confined basin, where the sedimentary budget remains closed. It evaluates the mechanism connecting between the primary and secondary axes. The study focuses on the Nile sedimentary system, across northeastern Africa and the eastern Mediterranean basin (primary axis) and the Levant depositional system (secondary sink). We hypothesize that since secondary river input into the Levant basin is negligible, the main secondary source is seafloor currents. The Levant Jet System (LJS) transported sediments from the Nile cone along the Levant margin at depths between 0 and 350 m, during the Holocene and until today. Once the LJS reaches its capacity to transport sediments, the surplus falls downslope to the deep basin. By integrating seismic and bathymetric data, this paper suggests a unifying mechanism integrating deposition, erosion and transport of sediments across the Levant margin and basin throughout the Quaternary. Results show that during both highstand and lowstand conditions the primary source-to-sink axis delivers sediments to the deep basin via south to north meandering channels. The LJS transports sediments that build the shelf, while unconfined overspills slide downslope to accumulate across the continental rise. However, when sea levels drop, the capacity of the LJS weakens. This results in a drastic decrease in sedimentation across the shelf and rise, accompanied by confined downslope turbidity flows into the deep basin. We conclude that seafloor currents serve as an immediate supplier from the mouth of the primary source (i.e. a major river) to the off-axis system. Variations in seafloor current dynamics and their capacity to transport sediments will be directly reflected in the secondary sink. The primary continental source is expected to have only an indirect effect on the secondary sink.

1. Introduction

The source-to-sink approach of sediment transport in the marine environment normally relates to an imaginary axis extending between land, the continental margin and the nearby basin (Fig. 1; e.g. Allen, 2008; Romans and Graham, 2013). Variability in sediment supply through time defines the efficiency of the source. It also represents the combined effect of the controlling factors, such as climate at the source. The development of a continental margin is measured through interactions between vertical tectonic shifts, relative sea level changes and net sediment supply rates. Sedimentation in the basin reflects the same factors, but in an indirect way. Lowstands expose the continental shelf to subaerial conditions, drawing closer land drainage to the continental slope, and thus facilitating a more direct supply of sediments to the basin. At the same time, the width of the submerged shelf becomes narrower. During highstands, a larger portion of the shelf is submerged, enabling seafloor currents to transport sediments along the shelf thus creating a barrier between land drainage systems and the continental slope. Drainage is disconnected from a direct pathway to the deep basin or is considerably limited (e.g. Covault et al., 2007). During both highstands and lowstands turbidity currents transport the sediments to the deep sea.

This source-to-sink approach oversimplifies the development of depositional environments located away from the main axis (Fig. 1). Longshore drift, for example, transports sediments towards *off-axis systems*, such as in the case of the northern shores of Washington State (Parks, 2015). However, in most cases local rivers along the course of the drift obscure its sedimentary contribution to the off-axis system. These systems are less likely to show a simple connection to factors controlling the primary sedimentary source. Here we examine the relations between primary and off-axis systems, and in particular their

* Corresponding author at: Dr. Mosses Strauss Department of Marine Geosciences, Charney School of Marine Sciences, University of Haifa, Abba Khoushy Ave 199, Haifa, 3498838, Israel.
E-mail address: schattner@sci.haifa.ac.il (U. Schattner).

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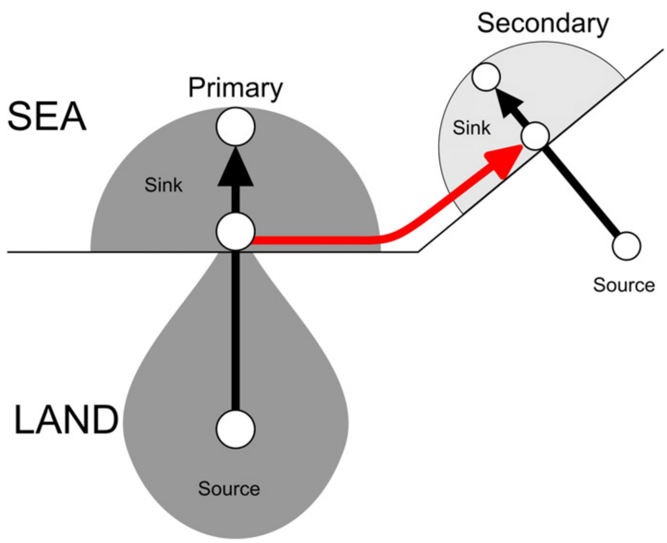

Fig. 1. Schematic illustration of a source-to-sink hierarchy. The source of the primary axis (dark gray tear-drop) is subjected to continental conditions, while the secondary source is negligible. Oceanic currents (red arrow) bypass and act as the secondary source.

connecting mechanism — sediment transport through oceanic currents and the corresponding pattern of accumulation. The study focuses on an off-axis system in a confined basin, in order to ensure that transported sediments remain within the general budget and do not leave the area. The research examines the thoroughly studied Nile sedimentary outlet into the eastern Mediterranean. Despite decades of research in this area, the dynamics of supply to the deep basin is virtually unknown. Similarly, sedimentation patterns during highstand and lowstand conditions have not been examined; nor have the sedimentary development of the continental rise and the imprint of turbidity flows on the morphology of the deep basin seafloor. This study aims at bridging these gaps and providing a unifying explanation for the sedimentary development of the Levant basin, eastern Mediterranean.

1.1. Geological setting

The Levant basin comprises the easternmost section of the eastern Mediterranean basin (Fig. 2). The main source of sedimentation is allochthonous terrigenous sediments arriving from the Nile River. This supply has been responsible for the construction of the Nile submarine fan in the southern Levant (MacGregor, 2011). Cyclonic oceanic currents transport a portion of the sediments along the Levant continental shelf (Buchbinder et al., 1993; Ben-Gai et al., 2005). This supply is conveyed along northern Sinai and the Levant margin (Goldsmith and Golik, 1980; Coleman et al., 1981; Inman and Jenkins, 1984; Rohrlicht and Goldsmith, 1984; Carmel et al., 1985; Stanley, 1989; Frihy et al., 1991; Frihy and Lotfy, 1997; Perlin and Kit, 1999; Almagor, 2000; Zviely et al., 2007; Hyams-Kaphzan et al., 2008), where it is joined by sediments from some minor local streams. Together they build the Quaternary succession (>1 km thick) of the Levant continental margin along the Nile littoral cell. This succession thins towards the continental rise and deep basin until reaching several tens of meters (Ben-Gai et al., 2005; Schattner et al., in press). Along this pathway, the width of the continental shelf narrows northwards from ~20 km to ~1 km offshore northern Israel (Ben-Avraham et al., 2006). Offshore the steep Lebanese margin, the width of the shelf is less than one km (Fig. 3; Carton et al., 2009).

A series of sea level lowstands were recorded in the global Quaternary record (Miller et al., 2011). They were also recognized in the stratigraphy of the Levant margin throughout the mid and upper Quaternary (13 sequences since 1.8 Ma; Lazar et al., 2016). These fourth order sequence boundaries were formed under forced regression conditions. Tectonic subsidence of the margin remained constant during most of the Quaternary, excluding a shift around 1 Ma (Ben-Gai et al., 2005). The rate of sediment supply from the Nile River into the Mediterranean decreased steadily during this period since its late Pliocene peak (MacGregor, 2011). On basis of this stability, Lazar et al. (2016) explained these seismic sequences primarily by sea level variations. However, the long stable trend mentioned by MacGregor (2011) will need to be evaluated as additional sedimentary data from the Nile outlet becomes available.

The most recent of these sequences recorded the sedimentary effect of relative sea level variations since the Last Glacial Maximum (LGM). During the LGM, global sea level stood at ~120 m below its present-day value (Fairbanks, 1989). The shoreline migrated basinwards to the edge of the continental shelf (Enzel et al., 2008), exposing it to subaerial erosion. The resulting unconformity appears in seismic reflection data as a prominent transition in acoustic impedance across the entire margin (Almagor, 2000; Lazar et al., 2016). Progradation of marine sediments continued across the shelf edge, which remained submerged. After the end of the LGM, sediment retrograded inland as sea level rose, until reaching its present height ~2–3 ka year BP (e.g. Sivan et al., 2001; Schattner et al., 2010). These sediments are comprised primarily of fine-grained Nile derived clays (Sandler and Herut, 2000). The post LGM sedimentary succession presents a full sequence yet to be truncated by lowstand erosion. It provides a modern analog for sediment accumulation during previous sea level fluctuations and the dynamics of seafloor currents that shaped their pattern.

Since the beginning of marine research in the Levant, longshore transport has been widely accepted as the only carrier of sediments. As such, it was regarded as an exclusive mechanism for the construction of the continental margin throughout the Plio-Pleistocene. Numerous studies provided theoretical (Neev, 1960; Goldsmith and Golik, 1980), bathymetric (Golik, 1993, 1997, 2002; Shoshany et al., 1996; Golik et al., 1999), geological (Buchbinder et al., 1993) oceanographic and geomorphological (Carmel et al., 1985; Perlin and Kit, 1999; Zviely et al., 2006) evidence to establish this perception. This transport, however, is limited to water depths of 30 m and extends ~400 m from the coastline. Despite this spatially limited view, the vast majority of studies rely on the longshore transport mechanism to explain sediment accumulation in deeper areas such as the continental slope, rise and basin floor (e.g. Box et al., 2011). They accept the stability of the system throughout the Plio-Pleistocene as a given fact (e.g. Horowitz, 1975; Gvirtzman and Buchbinder, 1978; Mart, 1993; Steinberg et al., 2011).

Longshore transport, however, is only one component in a larger sediment conveyer, the Levant Jet System (LJS, Fig. 9 in Schattner et al., 2015). An integrated interpretation of multibeam bathymetry, seismic and oceanographic data shows that the LJS flows along the Levant margin, between water depths of 0 and ~350 m (Fig. 2). It extends ~20 km from the present-day shoreline. LJS comprises three central water masses: Levant Surface Water (0–80 m deep), Levant Intermediate Water (80–130 m) and Atlantic Water (200–350 m). The northwards flow of the LJS is responsible for the transportation of sediments along the entire Levant margin. Their interaction with the seafloor causes erosion and reshapes its morphology (e.g. elongated truncations visible in seismic data and along-strike belts of sediment waves, respectively). These unique morphologies appear on the seafloor and are consistent with the subsurface structure of Holocene stratigraphy. Hence, Schattner et al. (2015) suggested that the initiation of the LJS during the Quaternary-Holocene transition reflected a gradual recovery of thermohaline circulation from glacial to interglacial conditions.

Numerous studies consider the local widening of the Levant continental shelf offshore Haifa bay (Figs. 2, 3) as the final location for deposition of Nile derived sediments and thus the northern limit of the Nile littoral cell (Pomerancblum, 1966; Nir, 1980; Inman and