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Research paper

Tidal meander migration and dynamics: A case study from the Venice Lagoon

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ABSTRACT

Meandering patterns are universal features of tidal landscapes and exert a critical influence on the dynamics of tidal channel networks and on the stratigraphy of the intertidal platforms they dissect. Despite their importance in landscape evolution and their ubiquity, tidal meanders have received less attention when compared to their fluvial counterparts. To improve current understanding of tidal meander migration and its possible stratigraphic implications, we analysed a sequence of aerial photographs and satellite images (from 1938 to present) of a meandering tidal channel in the Venice Lagoon, which experienced multiple cutoff events during its evolution. Migration rates of the considered bends are in the range of 0.06–0.17 m/y, whereas migration rates per unit width vary between 0.6 and 2.5% yr^{-1}. Detailed high-resolution geomorphological, sedimentological, and geochronological analyses were carried out for an abandoned meander bend, which experienced one of these cutoffs. Aerial photographs before and after the cutoff event (1938 and 1955, respectively) were used to infer a minimum velocity of migration (about 0.10 m/y). Sediment cores were also collected along a transect crossing through the meander neck in order to evaluate changes in grain size, sedimentation rates during the cutoff event, and gain further insight into the velocity of migration of meander bends. The spatial distribution of sedimentary facies (point-bar sand, oxbow lake, and salt-marsh mud), grain-size analyses, and ^{210}Pb and ^{137}Cs chronologies highlighted that meander cutoff occurred progressively around 70 years before present with an average migration rate of 0.25 m/year. Such a procedure to estimate meander migration rates from stratigraphic data reveals to be particularly useful in the absence of high-temporal resolution remotely sensed-images. The effectiveness of the methods used and the high spatial and temporal resolution of the data call for further investigations and analyses of the type proposed herein, furthermore highlighting the potential of the study area as modern analogue for ancient tidal deposits.

1. Introduction

Salt-marsh landscapes are commonly dissected by networks of meandering tidal channels that exert a strong control on the eco-morphodynamic evolution of these landscapes, facilitating the exchange of water, sediments and nutrients (D'Alpaos et al., 2005; Hughes, 2012; Coco et al., 2013). In spite of their prominence and wide occurrence, the characteristics and dynamics of meanders shaped by the periodically reversing tidal flows without fluvial influence, lack the detailed inspection that has been devoted to their fluvial relatives (e.g., Leopold and Wolman, 1960; Ikeda and Parker, 1989; Seminara, 2006; Zolezzi et al., 2012; Hooke, 2013) or to meanders developed in the fluvial-tidal transition zone (Ensign et al., 2014; Carling et al., 2015; Shschepetkina et al., 2016). Only a few papers analyzed the planimetric shape, morphometric characteristics, and morphodynamic evolution of tidal meanders. Ahnert (1960) first observed that the inner banks of estuarine meanders may display a distinctive cuspate shape due to the back-and-forth swinging of tidal currents that displaces the ebb (flood) current towards the seaward (landward) edge of the channel.

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Marani et al. (2002) studied the geometrical properties of tidal meanders through field observations and modelling interpretation. Solari et al. (2002) developed the first 3D model capable to predict the flow field and bed topography in weakly meandering tidal channels. Fagherazzi et al. (2004) coupled field observations and numerical modelling to analyze the effects of bidirectional flows on meander planform configuration and migration. Hood (2010) highlighted the role of deposition processes on tidal meander formation. Garotta et al. (2007) set up a laboratory experiment for a tidal meander, emphasizing along-channel changes in the relationship between bar–pool patterns and channel curvature. The effects of sediment cohesion and vegetation growth on tidal meander dynamics have also been analyzed (Garofalo, 1980; Gabet, 1998; Kleinhans et al., 2009), suggesting that highly cohesive soils on channel bed and banks and the stabilizing effect of marsh vegetation on the banks combine to render tidal meanders quite stable landscape features, less subject to the dynamic behavior that characterizes their fluvial counterparts. The depositional architecture of tidal meander bends has also been somewhat neglected (Choi and Jo, 2015) compared to the attention devoted to the fluvial realm (e.g, Allen, 1965; Bridge et al., 1986) and has mainly been approached using facies models (Barwis, 1978; De Mowbray, 1983; Choi et al., 2004; Choi, 2011), which assume the stratal geometries of tidal deposits to show marked similarities with those of their fluvial counterparts (Jackson, 1976; Brierley, 1991; Bridge et al., 1995; Pranter et al., 2007; Ghinassi et al., 2013, 2014).

A relevant question, with theoretical and practical implications, is whether or not morphodynamic and architectural models, mediated from the study of fluvial meanders, can be applied to tidal ones. The question arises from the observation of several fundamental differences between processes sculpting tidal and fluvial meanders, the most evident being periodically reversing flows in tidal settings. In addition, in tidal channels, landscape-forming discharges and strong flow velocities occur when tidal levels are just above (during the flood phase) or below (during ebb) the elevation of the marsh platform, whereas in rivers, high water levels and water depths are generally a proxy for large discharges. Rivers experience flood events characterized by high discharges which overlap to slowly varying discharges through the year, and high flow velocities can be maintained for relatively long time during floods that may last from several days up to a few weeks. By, contrast, tidal channels are characterized by highly variable discharges during a tidal period (hours), but are generally shaped by water fluxes that vary over a defined range of possible values. The signatures of these different processes can hardly be unraveled by the analysis of tidal meander planform configuration (e.g., Marani et al., 2002; Solari et al., 2002). However a recent detailed analysis of the internal architecture and sedimentary features of a tidal meander bend (Brivio et al., 2016) emphasized the existence of relevant differences imprinted in the sedimentary record, such as the absence of crevasse-splay deposits, the development of elongated pool zones, the overall symmetric distribution of sediment grain size along the landward and seaward sides of the bend, and the observed spoon-shaped geometry of the bar-top mud, resulting from the coupled effects of lateral migration and vertical aggradation (Brivio et al., 2016).

In addition, it is worth recalling that the occurrence of ecological and geomorphological processes that shape tidal landscapes (e.g., D'Alpaos et al., 2012) and which act at overlapping spatial and temporal scales (Feola et al., 2005) has challenged our capability of providing predictive numerical and experimental models of tidal-landscape dynamics (D'Alpaos et al., 2007; van Maanen et al., 2013; Vlaswinkel and Cantelli, 2011; Stefanon et al., 2012; Zhou et al., 2014), thus calling for further research efforts. Towards the goal of improving current understanding of the intertwined evolution of salt-marsh platforms and tidal meandering patterns cutting through them, the present study investigates the morphodynamic evolution of a meandering tidal channel in a salt marsh of the Northern Venice Lagoon (Italy; Fig. 1), which experienced various neck cutoffs along its reach (e.g., Hooke, 2004). We focus in particular on an abandoned meander bend, which experienced one of these cutoffs, using a multidisciplinary approach which combines: i) field observations; ii) mathematical modelling; and iii) sedimentary facies analyses. The aim of this paper is twofold. Through remote-sensing observations and modeling interpretation, we first describe tidal-meander migration and evolution, issues widely examined in studies of fluvial dynamics (Hickin and Nanson, 1975, 1984; Hooke, 1984; Lagasse et al., 2004; Frascati and Lanzoni, 2009, 2010; Parker et al., 2011; Eke et al., 2014) but which escaped detailed scrutiny in the tidal realm. Second, through the analysis of closely spaced sediment cores and the dating of significant sedimentary surfaces across the neck of the meander loop after the cutoff, we provide a new methodology to determine meander migration rates in the absence of high-temporal resolution aerial photographs.

2. Geological setting

2.1. The Venice Lagoon

The Venice Lagoon (Fig. 1A), located in the northwestern Adriatic Sea, is the largest Mediterranean shallow water body, with an area of about 550 km^2 (length and width of the tidal basin are about 50 km and 10 km, respectively; see Fig. 1A) and a mean water depth of 1.0–1.5 m. The tidal regime is semidiurnal and microtidal, with an average range of about 1.0 m and maximum water excursions at the inlets of $\pm$0.75 m around mean sea level (hereinafter MSL), which can suddenly be increased by meteorological forcing (Carniello et al., 2016). The lagoon is separated from the Adriatic Sea by two narrow land strips about 0.5 km wide, while three inlets (Lido, Malamocco, and Chioggia) grant communication and active water exchange between the lagoon and the sea (Fig. 1A). The Venice Lagoon is hosted in the coastal sector of the Venetian Plain foreland basin (Massari et al., 2009). During the early Pleistocene, this basin experienced a change from deeper-water, turbiditic to shallow-marine deposition (Massari et al., 2004), accumulatig ~750 m of shallowing-upward deposits. During the Last Glacial Maximum (LGM), the Brenta River megafan occupied most of the present Venice area (Fontana et al., 2014). The Venice Lagoon formed as a consequence of the Holocene transgression, which promoted flooding of the LGM alluvial plain with formation of lagoon – estuarine – barrier systems on the Northern epicontinental Adriatic shelf (Zecchin et al., 2009).

2.2. The study site

The study site is located in the San Felice salt marsh (Fig. 1B), in the northern part of the Venice Lagoon, which is amongst the most naturally preserved portions of the Lagoon (Marani et al., 2003; Rizzetto and Tosi, 2011, 2012). The marsh is characterized by an average elevation of about 0.26 m above MSL and is mainly colonized by four halophytic species: *Spartina maritima, Limonium narbonense, Sarcocornia fruticosa and Juncus* spp. (Marani et al., 2006). The San Felice salt marsh is considered to be a stable marsh (Rizzetto and Tosi, 2011; Roner et al., 2016) whose accretion rate of about 3 mm/y (Day et al., 1998) is in approximate equilibrium with the local rate of relative sea-level rise of ~3 mm/y (Carbognin et al., 2004; Strozzi et al., 2013). The present study focuses on point-bar deposits associated with an abandoned meander loop oriented NW-SE (Fig. 1C), formed by a 6-m-wide