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The role of neo-tectonics in the sedimentary infilling and geomorphological evolution of the Guadalquivir estuary (Gulf of Cadiz, SW Spain) during the Holocene

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ABSTRACT

A multidisciplinary analysis of cores and geomorphic patterns in the marshes of Doñana National Park (SW Spain) has yielded new evidence regarding the sedimentary infilling and geomorphological evolution of the Guadalquivir estuary during the Holocene. The sedimentation and geomorphological disposition have been strongly conditioned by neotectonic activity along a set of SW-NE alignments, interrupted by other alignments that follow E-W and NW-SE directions. The most conspicuous of the SW-NE alignments is the Torre Carbonero-Marilópez Fault (TCMF). South of this fault, the estuary experienced a marked subsidence from about 4000 to 2000 cal. yr BP through a series of sedimentary sequences of retrogradation and aggradation within the context of relative sea-level rise. From c. 2000 cal. yr BP to the present the subsidence has remained relatively dormant, with progradation of the littoral systems and infilling of the marshland progressing within a context of sea-level stability. Our results reveal that neotectonic activity is a critical factor that must also be reckoned with in any attempt to understand the Holocene geomorphological evolution in the Guadalquivir estuary.

1. Introduction

It is well known that estuaries evolve as the result of the interaction between geomorphological structures and dynamic processes that are marine as well as riverine; this interaction adds up to processes that are inherently estuarine. Local modifications also intervene; they derive from relative sea-level changes, climate conditions and human activities (Jackson, 2013). Neotectonic activity (hereafter referred to as neotectonics) ought to be included as a factor as well; in combination with the other parameters, it may cause changes in the sedimentation rates, result in the creation of new geomorphological features (spits, dunes, cheniers, marshes, levees, alluvial soils), sea-level oscillations (Kennedy, 2011; Yeager et al., 2012; Feagín et al., 2013) and associated tsunami and storm inundation (Morton et al., 2007; Nichol et al., 2007). The subsidence lowers tidal salt-marshes and fertile lowlands below the level of the sea, which thereafter deposits layers of sediments on the former sub-aerial surfaces until fresh alluvial sedimentation overrides these layers, only to be buried below sea level in the next subsidence cycle (Bolt, 2003). Because of relatively rapid developments such as these, neotectonics must be taken into account in any geomorphic and sedimentological analysis that aims to reconstruct past environmental evolutions in littoral areas close to zones of contact between tectonic plates (Rey and Fumanal, 1996; Uluğ et al., 2005).

The Mediterranean basin presents numerous examples of neotectonic activity that conditions the morphodynamic evolution of the coastlines, specifically vertical displacements related to the collision of the African and Eurasian plates; as in Apulia, Italy (Mastronuzzi and Sansó, 2012), the south-east of the Aegean Sea (Uluğ et al., 2005), and the Gibraltar Strait (Zazo et al., 1999c). Comparable scenarios

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have been identified along the Pacific coasts of North and South America (Atwater et al., 1992; Muhs et al., 1992; Bolt, 2003; Ota and Yamaguchi, 2004). In North America, for instance, cycles of subsidence of the coastline have been reconstructed in connection with the punctuated downward movement of the North American plate vis-à-vis the Pacific plate in the Cascadian subduction zone (Nelson et al., 2006; Shennan and Hamilton, 2006). Across the Western hemisphere, in the Gulf of Mexico, active fault motion has been suggested as a prime mover of the recent evolution of the coastline (Yeager et al., 2012; Feagín et al., 2013). The multidisciplinary examination of cores extracted from estuaries, lagoons, salt-marshes, coastal barriers and deltas has revealed a great deal of information about these evolutions (Vött, 2007; Sorrel et al., 2009).

In the present paper we offer the results of a comprehensive geological study of the geomorphological patterns recognized in the Guadalquivir estuary, which have been poorly researched to date. The study included continuous core-drilling and subsequent lithostratigraphic, paleontological and mineralogical analyses, as well as archaeological probing and radiocarbon determinations. We contend that sustained neotectonic activity in the estuary, as in geologically comparable areas elsewhere in the world, has contributed significantly to the sedimentary infilling and geomorphological configuration of the basin during the Holocene, marking it out from the other estuaries in the Gulf of Cadiz. Our results, in effect, indicate that neotectonics has been a critical factor in the evolution of the entire Atlantic–Mediterranean linkage coast after the transgressive maximum of the Atlantic Ocean; consequently, it must be so taken into account in any future understanding of such evolution. We aim primarily at defining a new palaeogeographic framework in which to ground fresh multidisciplinary research in an area, such as Doñana National Park and its environs, that is so internationally attractive from a natural as well as a cultural standpoint.

2. Geological and morphodynamic setting

The Iberian Peninsula lies at the southwest corner of the continental component of the Eurasian plate, right across the northern boundary of the African plate or Azores-Gibraltar fault zone. The present geological structure of the Gulf of Cadiz is the result of the European–African plate convergence motion, dextral strike-slip along the Azores–Gibraltar Plate Boundary (Medialdea et al., 2009). This plate convergence lasted from Mid Oligocene up to Late Miocene times and then continued with slow Late Miocene to Recent NW convergence (Rosenbaum et al., 2002). Westward drift and collision of the North African and southern Iberian margins in the Early–Middle Miocene caused the radial emplacement of huge allochthonous masses (the so-called “Olistostrome Unit”) in the Guadalquivir Basin (Iberian foreland) and the Gulf of Cadiz (Torelli et al., 1997; Maldonado et al., 1999). Such emplacement on the Atlantic realm has been related to the western migration of the Alborán terrain as a consequence of a once active subduction zone (Royden, 1993; Iribarren et al., 2007). Alternatively, Gutscher et al. (2002) proposed that this subduction is still active. This complex geodynamic evolution is recorded in the architecture and tectonic structure of the continental margin of the Gulf of Cadiz and likely in the sedimentary infilling and geomorphological evolution of the littoral landforms. In connection with neotectonic activity in the area, tsunamis – occasionally of rather large magnitude – are a type of high-energy event that affects the Gulf. There is a large body of data on this type of event occurring periodically over the past 7000 years (Lario et al., 2011).

The Gulf includes a number of estuaries, all of them partly enclosed by coastal barriers or spits. Borings taken at some of the largest of these estuaries have provided cores that are the basis for the current understanding of the sedimentary evolution of this coast of southwest Iberia during the Late Pleistocene as well as in the Holocene. The most consistent and reliable results to date have been obtained from borings done in the estuaries of the Guadalete and Odiel-Tinto rivers (Goy et al., 1996; Borrego et al., 1999; Dabrio et al., 1999, 2000). Yet the largest estuary in the Gulf, by far, is the estuary of the Guadalquivir River, enclosed by two spits (Doñana and La Algaida) (see Fig. 1). The entire area encompasses one of the largest wetlands (50,720 ha) in Europe as well as Doñana National Park, a UNESCOMAB Biosphere Reserve. Paradoxically enough, the infilling of this large basin in the course of the Holocene has drawn but scant interest. Significant contributions have only been a fragmentary analysis of a long core (Zazo et al., 1999a; Lario et al., 2001; Pozo et al., 2010) and research on the period between the Upper Pliocene and the Quaternary which has failed to concentrate on the evolution during the Holocene (Salvany et al., 2011).

Paucity of dated cores has combined with a complex tectonic activity in the basin to render reconstructions of the fossil infill difficult (Zazo et al., 2008; Rodríguez-Ramírez et al., 2012). Research on the Holocene features has mostly addressed the geomorphology of the surface formations, although it has resulted in a number of models of palaeoclimates, palaeoenvironments and sea-level fluctuations charted on a sound chronological database (Menanteau, 1979; Zazo et al., 1994; Rodríguez-Ramírez et al., 1996; Rodríguez-Ramírez, 1998; Lario et al., 2001; Ruiz et al., 2004, 2005; Rodríguez-Ramírez and Yáñez, 2008). The same formations have been pointed out to in the search for pre-Roman archaeological sites in the estuary and its vicinity (Bonsor, 1922, 1928; Fernández Amador de los Ríos, 1925; Schulten, 1945; Corzo, 1984; Kühne, 2004). The chronological database elucidates a number of periods of climate, natural environment and sea-level changes, as well as phases of progradation and erosion of beaches, that unfolded after the transgressive maximum of the Atlantic Ocean c. 6500 ^{14}C yr BP (Zazo et al., 1994). As refined from studies of spit systems elsewhere in southern Iberia, on the Mediterranean as well as on the Atlantic seaboard (Zazo et al., 1994, 2008; Lario et al., 1995, 2001; Goy et al., 1996, 2003; Rodríguez-Ramírez et al., 1996; Dabrio et al., 1999; Ruiz et al., 2004, 2005), the database now includes as many as six discrete phases of progradation (H_1 to H_6) following such a transgressive maximum, each phase separated from the next by an erosive surface or a particularly large swale, or both, known as a “gap.” Oddly enough, the subaerial record in the spit system of Doñana – the most extensive in the Gulf of Cadiz, fronting the Guadalquivir estuary – and that of La Algaida register only part of the H_5 phase (the oldest beach ridges exposed having been dated to c. 2000 cal. yr BP) plus the entire H_6 phase, from c. 500 cal. yr BP to the present (Zazo et al., 1994; Rodríguez-Ramírez et al., 1996). Evidence of phases H_1, H_2, H_3 and H_4 is missing. In stark contrast, the Guadalete and Tinto-Odiel estuaries present exposed prograding units from the H_3 phase to the present (Goy et al., 1996; Dabrio et al., 2000; Zazo, 2006; Zazo et al., 2008) (Fig. 2).

Behind the Doñana spit system sits a large marshland area (185,000 ha) – the heart of the Guadalquivir estuary – that is the end product of the sedimentary infilling of the original Holocene basin or palaeoestuary by the Guadalquivir and other rivers, a process that developed in the manner of a finger-like delta formation extending in a low energy environment favoured by the growth of the large littoral barriers that isolated the palaeoestuary from the sea (Rodríguez-Ramírez et al., 1996; Rodríguez-Ramírez, 1998). With a low gradient, features in the marshland include various muddy morphologies (levees, channels, point-bars) that have resulted from intense fluvial action, extensive sandy and shelly ridges (cheniers) resting on the clayey sediments, and marine processes operating against the barriers (Rodríguez-Ramírez et al., 1996). The wide-ranging chenier plain formed during two phases of accumulation: from c. 4200 to 2800 cal. yr BP and from c. 1400 to 1000 cal. yr BP (Rodríguez-Ramírez and Yáñez, 2008). No surface landforms of the same characteristics dating to a phase in between, of some 1400–2800 yr BP, have been encountered (Rodríguez-Ramírez and Yáñez, 2008). The reason for this anomaly must be found in the tectonic complexity that affects the Holocene features.

Beneath the marshland sediments, Plio-Quaternary deposits as much as 300 m thick unconformably cover Late Miocene-Early Pliocene blue marls (Salvany and Custodio, 1995) as well as the Olistostrome. As remarked by Armijo et al. (1977) and Viguier (1977), the