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Delta dynamics: Effects of a major earthquake, tides, and river flows on Ciénega de Santa Clara and the Colorado River Delta, Mexico

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ABSTRACT

The intertidal portion of Mexico's Colorado River Delta is a dynamic environment subject to complex interactions of tectonic, fluvial, and tidal forces at the head of the Gulf of California. We review the historical interactions of these forces, use sequential satellite images, overflights, ground observations, and interferometric synthetic aperture radar (InSAR) data to study the effects of the 2010 Mw 7.2 El Mayor-Cucapah Earthquake on changing patterns of tidal inundation within the Delta, and assess effects of these changes to the fluvial/hydrological regime of the Colorado River estuary and nearby Ciénega de Santa Clara wetland. The objectives of this study are to highlight for environmental scientists, land managers, and ecological engineers the contribution of tectonic forces in shaping the intertidal Delta environment and to provide information on the effects of the 2010 earthquake which will be of practical value in planning and designing management measures and restoration projects for the estuary and Ciénega.

The Colorado River estuary is at present blocked by a tidal sand bar which restricts access by marine species to the upper estuary and obstructs the flow of fresh water into the lower estuary. Located 13 km east of the estuary, the Ciénega is a 6000 ha wetland supported by agricultural drain water from Arizona and Mexico. South of the Ciénega is the Santa Clara Slough, an unvegetated 26,000 ha basin subject to periodic inundation from the northern Gulf's high amplitude tides, which have historically reached the margins of the Ciénega several times each year.

The El Mayor-Cucapah earthquake ruptured the previously unknown Indiviso Fault which extends into the intertidal zone just west of the Ciénega. The Ciénega experienced only minor surface deformation having no direct effects to the wetland. Most of the significant ground movement and surface deformation occurred west of the Indiviso Fault adjacent to the estuary, where portions of the intertidal flats underwent extensive liquefaction, northward coseismic displacement and post-seismic subsidence. These surface deformations changed the pattern of tidal inundation, triggering development of a new system of natural tidal channels and creating conditions favorable for installation of projects to restore connectivity between the upper and lower estuary. The changed pattern of tidal inundation may also have contributed to an observed reduction in the occurrence of tidal flooding along the southwestern margin of the Ciénega following the earthquake.

1. Introduction

1.1. The confluence of powerful tectonic, tidal, and fluvial forces

For the past 5 to 6 million years, the Colorado River has flowed into the Gulf of California near the northern end of a great rift depression formed by a system of transform faults and seafloor spreading centers at the boundary of the North American and Pacific tectonic plates (Alles, 2011). The area marks a transition zone between the right lateral movement of the San Andreas Fault system and the spreading movement of the East Pacific Rise, which is wedging the Pacific plate (including the Baja Peninsula and southwestern California) away from the North American plate (Burnett et al., 1997). The river has deposited $2.2–3.4 \times 10^5$ km^3 of eroded Colorado Plateau sediments in a delta cone which has partially filled the rift depression, isolating its landlocked but mostly sub-sea level northern extension (the Salton Trough) from the southern portion occupied by the Gulf (Dorsey, 2010). The Gulf's long, narrow form

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Fig. 1. Main features of the Colorado River Delta in Mexico showing the Ciénega de Santa Clara, Santa Clara Slough, Cerro Prieto transverse fault (CPF), the newly discovered Indiviso Fault zone (IF) and other transverse faults (OF) that ruptured during the April 2010 M_w 7.2 El Mayor-Cucapah Earthquake. The epicenter was 45 km northwest of the study area.

contributes to high amplitude (up to 8.5 m) tides at the mouth of the Colorado River, resulting in an extensive intertidal plain where the low-gradient (about 0.016 m/km) delta cone approaches the sea (Thompson, 1968).

The Ciénega de Santa Clara, a 6000 ha wetland supported by agricultural drain water from Arizona and Mexico, is located 50 km south of the Arizona-Sonora border and 20 km north of the Gulf (Fig. 1). The wetland is situated at the northern edge of the intertidal zone in low ground along the Cerro Prieto transform fault, which marks the eastern margin of the Delta plain and has been considered the principal plate boundary fault in this area (Hauksson et al., 2010).

The river's flow has been anthropogenically manipulated over the last century by implementation of water storage and diversion projects upstream in the Colorado River Basin and irrigation and flood control projects locally in the Mexicali and San Luis valleys. Prior to this manipulation, most of the river's annual flow of 14.5–20.7 × 10^9 m^3 reached the Delta (Fradkin, 1996), delivering about 160 million metric tons of sediment each year (Van Andel, 1964). In most years since the completion of upstream projects, only a fraction of the 1.9 × 10^9 m^3 of Colorado River flow allocated annually to Mexico has reached the Delta (Fradkin, 1996), although additional flood releases averaging about 5.2 × 10^9 m^3 annually arrived during the period 1983–1998 when upstream reservoirs were full (Glenn et al., 1999). Most river sediments are now trapped in upstream impoundments and no longer reach the Delta (Thompson, 1968). While water management decisions have served mainly to deprive the Delta of water, they have also provided a relatively constant (though never guaranteed) source of water for the Ciénega, which has developed into the largest wetland on the Mexican portion of the Delta since the initiation of agricultural wastewater delivery from Arizona in 1977 (Flessa and García-Hernández, 2007; Glenn et al., 1996; Greenberg and Schlatter, 2012). The Ciénega is located at the northern end of the Santa Clara Slough, a shallow, enclosed 26,000 ha intertidal basin situated between the fault-controlled Gran Desierto Escarpment

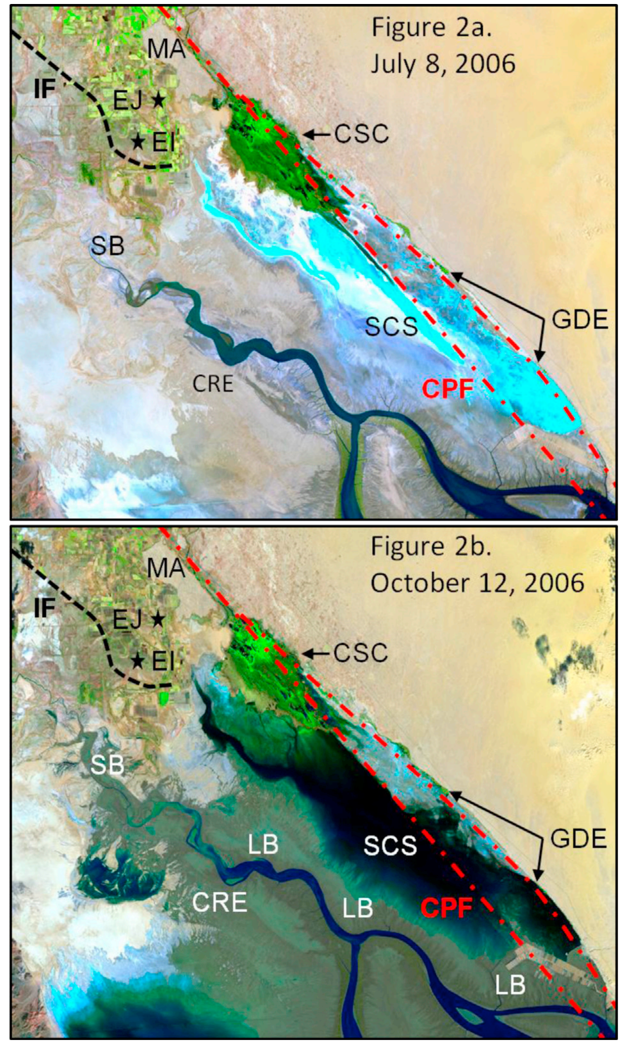

Fig. 2. The lower Colorado River Delta study area. CSC: Ciénega de Santa Clara. SCS: Santa Clara Slough MA: Mesa de Andrade GDE: Gran Desierto Escarpment CPF: Cerro Prieto Fault (red dashed line) CRE: Colorado River Estuary SB: Tidal sand bar LB: Fluvial levees/tidal berms IF: Indiviso Fault (black dashed line) EI: El Indiviso EJ: Ejido Johnson.

on the east and natural fluvial levees/tidal berms bordering the Colorado River estuary and Gulf coast on the west and south (Fig. 2).

1.2. Earthquake history

The Cerro Prieto Fault in the Ciénega/Slough area has probably ruptured on several occasions in 120 years (Anderson and Bodin, 1987; Felzer and Cao, 2008; Munguia et al., 1988). An 1891 earthquake (M 6.0) caused the collapse of a 100-foot section of bluff at the north end of the Mesa de Andrade (Fig. 2), and opened up three large cracks, each over 450 m in length along the banks of "Salt River" in the fault depression on the east side of the mesa (Strand, 1981). The alluvial plain west of the river (which includes the area of the modern community of El Indiviso) was reported to have been more severely disturbed, with wider and more frequent cracks and trees thrown down in great numbers (Strand, 1981). Sykes (1937) observed extensive structural damage and ground fissures at the Lerdo Colony on the west side of the Mesa de Andrade following a 1903 quake (M 6.6). Ground displacement from a 1934 quake (M 7.0) has been surmised from fresh fault scarps visible in 1935 aerial photographs of the Santa Clara Slough (Biehler et al., 1964;