INTEGRATED GEOLOGICAL AND GEOPHYSICAL STUDIES OF THE INDIO MOUNTAINS AND HUECO BOLSON, WEST TEXAS

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Dedication

To my lovely family…

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by

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DISSERTATION

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Abstract

This dissertation consists of two different projects. The first project describes the results of an outcrop based sequence stratigraphic study of the Albian Cox Sandstone in the Indio Mountains of west Texas. The depositional environment of the Cox Sandstone ranges from shallow marine to the coastal plain deposited in four sequences where sequence 1 and sequence 2 consists of transgressive system tracts (TST) followed by highstand system tracts (HST). The highstand system tract (HST) is missing in sequence 3 and the transgressive systems tract is missing in sequence 4. The Cox changes in thickness from 320 m in the northern end of the outcrop belt to 365 m in the southern end. This thickness change is accommodated during transgression where shales drape topography that is actively being shaped by faults and block rotation recorded in exposed growth strata. During Highstand, coarse fluvial-deltaic systems truncate shales on topographic high levelling the topography. Systems tracts and sequences change thickness due to block rotation and erosion as well as deposition from a point source near the center of the outcrop belt. The second project involves the integrated study of gravity and well log data in the northern Hueco bolson. The objective of this study is to demarcate subsurface faults that appear to control the locations of fresh and brackish water. In this study 28 gravity anomalies were identified that correlate with previously mapped (Collins and Raney, 2000) and new faults, and some of them can be extended further south to south east to join with previously mapped faults by Collins and Raney (2000) and Marrufo (2011). Structural cross sections of well logs also suggest that at least some faults are present between them. The four depositional environments inferred from the gamma log responses and their stacking patterns are consistent with the previous interpretation of Doser and Langford (2006) and Marrufo (2011).

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SECTION 1

Outcrop Study of Sequence Stratigraphic Framework and Depositional Environment: the Cox Sandstone of the Chihuahua Trough, the Indio Mountains, Texas, USA

1.1 Abstract

Excellent exposure of the Albian Cox sandstone in the Indio Mountains of west Texas provides outcrop opportunities to study sequence stratigraphic framework of a rift basin margin. The depositional environment of the Cox ranges from shallow marine to the coastal plain deposited in four sequences where sequence 1 and sequence 2 consists of transgressive system tracts (TST) followed by highstand system tracts (HST). The highstand system tract (HST) is missing in sequence 3 and the transgressive systems tract is missing in sequence 4. The Cox changes in thickness from 320 m in the northern end of the outcrop belt to 365 m in the southern end. This thickness change is accommodated during transgression where shales drape topography that is actively being shaped by faults and block rotation recorded in exposed growth strata. During Highstand, coarse fluvial-deltaic systems truncate shales on topographic high levelling the topography. Systems tracts and sequences change thickness due to block rotation and erosion as well as deposition from a point source near the center of the outcrop belt.

1.2 Introduction

This study describes the sedimentary response to complex intrabasinal deformation in exposed Cretaceous rift sediments. We use a sequence stratigraphic approach to document facies distributions and patterns of sedimentation that accommodate faulting and expansion of the section. Many studies of rift deposition describe the alluvial fan and lacustrine fill deposited during the early filling of rift basins. This paper describes a later-stage of rifting, during which transgression has created a narrow sea, which is effected by eustatic as well as tectonic events.

The Cretaceous Border Rift System has been used to describe a Mesozoic extensional terrane with basins that formed along the US-Mexico border between Texas and eastern California (Dickinson & Lawton, 2001). At least the western part of this system records a two-phase deformation history with an unconformity separating Jurassic from Early Cretaceous. These basins are typically deep and narrow. The Chihuahua Trough, the rift basin that forms the focus of this study, contains 5 km of Cretaceous strata (Haenggi, 2001). The Chihuahua trough portion of the rift is bounded by Diablo and Aladama Platforms in the North and South respectively (Haenggi, 2001) (Fig. 1.1). The Indio Mountains, which are located approximately 120 miles southeast of El Paso, expose the northern flank of this extensional basin (Fig. 1.1), and offer exposures that link sedimentation and tectonism.

1.3 Regional Geology

The Chihuahua trough is a NW-SE elongated mid-Mesozoic extensional basin. Though many authors used "Chihuahua trough" for the first time in 1964 (Bridges, 1964; Deford, 1964; Pearson, 1964), their extent of trough was uncertain. Later, Gries and Haenggi (1970) defined the Chihuahua trough as "a relatively narrow, northwest-southeast trending negative feature flanked by the Aldama and Diablo Platforms". More precisely, (Haenggi, 2001, 2002) defined Chihuahua trough as the area of north-eastern Chihuahua and adjacent parts of Texas, New Mexico and Sonora placing north-western limit along the 109th Meridian, and arbitrary southern boundary at the edge of North American craton. Lawton and Mcmillan (1999) and Dickinson and Lawton (2001) introduced the concept of the Border rift system, and included the Sabinas basin, Chihuahua trough, Bisbee basin, and McCoy basin in their Border rift system (Fig. 1.1). However, the absence of Jurassic igneous activity in the Chihuahua trough led Haenggi (2002) and Haenggi and Muehlberger (2005 to treat the Chihuahua trough as a different basin than the coeval Sabinas and Bisbee basins. A recent study from Peryam et al. (2012) also described the Chihuahua trough as a part of the Border rift system.

The Chihuahua trough initiated as a rift basin during the Jurassic (Oxfordian) and extended from the Gulf of Mexico to Southern Arizona along the international border between the United States and Mexico (Haenggi, 2002). The interpretation of tectonic setting of the basin varies widely (Lawton & Mcmillan, 1999) and Dickinson & Lawton, (2001) advocated a back-arc basin setting with Cordilleran slab rollback as a mechanism for basin development. Lawton & McMillan (1999) proposed a three phase tectonic model to explain the borderland rift system: 1) normal subduction; 2) early slab retreat, lithospheric magmatism, and basin formation; and 3) rapid basin subsidence and asthenospheric magmatism. Stern and Dickinson (2010) have described the Gulf of Mexico as a Jurassic back-arc basin, and the Border rift system as intra-arc basin, and related their association with Nazas magmatic arc. Anderson and Nourse (2005) disagreed with the backarc model for the Border rift system, and inferred a sinistral transtensional basin system along the Mojave-Sonora megashear (Anderson & Silver, 1979). They infer that initial sedimentation within the trough was controlled by northwest and east-striking faults, and formed en route to pull-apart basin development at releasing steps along left-lateral faults (Anderson & Nourse, 2005). In contrast, Haenggi and others (Haenggi, 2001, 2002; Haenggi & Muehlberger, 2005) have proposeda dextral transtensional model to explain the evolution of the Chihuahua troughwith the Chihuahua trough forming as a right-lateral pull apart basin during the Oxfordian (159-156 Ma). They related dextral motion to counter clockwise rotation of the North American plate in response to opening of the Atlantic Ocean (Haenggi, 2002; Haenggi & Muehlberger, 2005). Most recently, in describing the Bisbee Basin, Peryam et al. (2012) noted that it, like the Chihuahua trough, exhibits a two-phase deformation and ascribed rifting to the Jurassic phase and a back arc setting to the Middle Cretaceous phase, and noted a prominent lower Cretaceous unconformity. In the Chihuahua Trough portion of the system, Jurassic sediments are largely buried and Neocomian (Early Cretaceous) sediments are not exposed.

The strata exposed in the study area are from the later phase of extension, which began in the Aptian. During the Aptian through the Cenomanian, over 5 km of sediments were deposited

immediately south of the study area. This pattern of deposition came to an end during the Turonian, when increased clastic deposition and the formation of a clastic-dominated basin overlapped the edge of the trough. Mack (1987) described a similar change in deposition that occurred in the Cenomanian in Southern New Mexico to the west of the study area.

During the Laramide orogeny (84 to ~45Ma in this region), the Chihuahua trough was inverted, leading to compression and shortening in the region (Deford, 1958; Henning, 1994; Haenggi, 2002). The Laramide fold belt in Texas and Chihuahua is commonly called the Chihuahua tectonic belt (Deford, 1958; Gries, 1980). Jurassic evaporites of La Casita Formation are thought to form the principal decollement of the Chihuahua tectonic belt above which, the Cretaceous rocks were transported to the Northeast (Haenggi, 2002). Based on the presence of Jurassic salts, several authors advocated evaporite tectonics as the primary control for later Laramide structures. (Haenggi & Gries, 1970; Gries & Haenggi, 1970; Drewes, 1978; Gries, 1980; Dickerson, 1985; Haenggi, 2002).

In the study area several thrust faults exhumed the Aptian through Cenomanian rift fill (Reaser and Underwood, 1980; Underwood, 1980; Carciumaru and Ortega 2008; Page, 2011). Recent restoration of the thrust system indicates that two thrust sheets expose different part of the rift basin (Page, 2011). The lower, thrust sheet was displaced 7 km from the Southwest, and contains a thinner, more basin margin stratigraphy, whereas the upper thrust plate exposes thicker and more distal strata from 18 km to the Southwest (Page, 2011). The area was exhumed during the Paleogene and overlain by Paleogene volcanic rocks but during the Neogene, the Mesozoic strata were re-exhumed along north-northwest trending extensional faults that formed the present-day Indio Mountains. These faults cut across the thrusts and the depositional trends of the Chihuahua trough sediment, exposing both thrust plates. The result of this complex depositional and tectonic history is an outcrop belt that exposes two slices of the Cretaceous Rift fill in panels oblique to the Border Rift margin. This study is a detailed examination of one formation, the Cox Sandstone along one of these panels, showing detailed changes related sedimentation during the Cretaceous rifting.

1.4 General Stratigraphy

The stratigraphy of the Chihuahua trough differs from basin margin to basin center (Cordoba *et al.*, 1970; DeFord & Haenggi, 1971; Haenggi & Gries, 1970). The Mesozoic succession varies in thickness from 200 m in the basin margin (King, 1965; Albritton & Smith, 1965) to 4,700 m in the basin (Haenggi, 2002). Significant facies variations and accompanying lithostratigraphic nomencclature variations occur in association with these thickness variations (Fig. 1.2). The oldest rocks exposed in the Chihuahua trough are the Jurassic La Casita formation. Evaporites deposits (Tithonian-Necomian) in the Chihuahua trough are assigned as "unnamed gypsum" (Spiegelberg, 1961) or "unnamed evaporites sequences" (DeFord and Haenggi, 1970) or "Loma Blanca Formation" (Cordoba *et al.*, 1970). The rocks of the Indio Mountains were deposited toward the basin margin, where (Underwood, 1975) described the Yucca Formation, Bluff Mesa Formation, Cox Sandstone, Finlay Limestone, Benevides Formation, Espy Limestone and Buda Limestone of the Cretaceous (Fig. 1.2).

Interestingly, Kimmeridgian to upper Aptian rocks are absent in the Chihuahua trough margin. The origin of this unconformity has been uncertain by but Peryam *et al.*, (2012) showed that in the Bisbee Basin this interval was an angular unconformity separates the Lower Cretaceous strata from Upper Jurassic rocks (Peryam *et al.*, 2012). If the Bisbee basin and Chihuahua trough are the parts of same Border rift system, these data suggest an unconformity separates Upper Jurassic rock from Lower Cretaceous strata in Chihuahua trough and the Lower Cretaceous assemblage records tectonic events distinct from the Jurassic assemblage of the basin.

1.4.1 COX SANDSTONE

The Cox Sandstone (Campbell, 1959) outcrops in many localities in Trans-Pecos Texas and Mexican region. Richardson (1904) used the term "Cox" for first time in his Finlay Mountains section. Though this unit is easily traced throughout the Chihuahua trough, the lateral variation in lithology and thickness is conspicuous. DeFord and Haenggi (1971) correlated the

lower part of the Cox sandstone with the Glen Rose formation in the upper part of the Trinity Group of Central Texas, and the upper part with the lower part of the Fredericksburg Group.

Deford and Haenggi (1970) also proposed the name Lagrima Formation for the lateral equivalent of the Cox sandstone in Sierra Lagrima or Sierra del Hueso area. The overall thickness of the Lagrima formation in Sierra Lagrima is estimated to be 1,000 to 1,100 m (DeFord and Haenggi, 1970). Haenggi (1966) studied the relationship between Cox sandstone and the Lagrima Formation in El Cuervo area, northeastern Chihuahua, Mexico; and found an abrupt change in lithofacies from predominant sandstone to predominant limestone from the Cox Sandstone to the Lagrima Formation.

The minimum measured thickness of the Cox Sandstone is 51 m (135 ft) in the Kent area (Brand & Deford, 1958), and the maximum is 785 m in El Cuervo area (Haenggi, 1966). Hicks (1997) studied the depositional environments and diagenesis of the Cox Sandstone in the Finlay Mountains area, where he measure 185 m maximum thickness and divided the sandstone into four lithofacies. Several authors, studying ranges south and west of the study area, divided the Cox into upper and lower sandstones, separated by a limestone member (Haenggi, 1966; Deford and Haenggi, 1970; Jones and Reaser, 1970). The upper contact of the Cox with the overlying Finlay Limestone has been described as both gradational and unconformable (Brunson, 1954; Wade, 1954; Albritton and Smith, 1965; Haenggi, 1966; Underwood, 1975). However, as will be described below, the lithologic contact between the formations is an intertonguing contact within a sequence.

Regionally, the Cox Sandstone overlies lithologically varied strata that are known as the Bluff Mesa Formation, Quitman Formation and Campogrande Formation in Trans Pecos Texas, the Beningo Formation in Northern Mexico (Underwood, 1962; Haenggi, 1966; Hicks, 1997). Outside the Border Rift, the Cox unconformably overlies Permian limestone (Mount, 1960; Albritton and Smith 1965). Within the study area, the Cox rests on a well-exposed sequence boundary that separates it from the underlying limestones of the Bluff Mesa Formation.

The Cox and its correlative formations have been ascribed to the middle Albian in age (Underwood, 1962; Albriton and Smith 1965). The initial marine transgression into the Indio Mountains area occurs just below the Bluff Mesa Formation, in the underlying upperYucca Formation. The Bluff Mesa Formation is dominantly a marine deposit, but deposition did not extend beyond the margins of the subsiding Chihuahua Trough/Border Rift (Haenggi, 1966; Cordoba, 1969). The Cox Sandstone and overlying Finlay Limestone mark the initial transgression beyond the margins of the Border Rift as part of a regional transgression (Cheatham, 1984). Although the Cox extends across the Diablo Plateau, it thins from 365 m in the study area to 60 m thick outside the Rift (Albritton and Smith, 1965). Because it thickens within the trough, it is ideal unit to study the effects of tectonism on a unit that extends beyond local fault blocks.

1.5 Methods

A detailed outcrop analysis provided the data to distinguish the facies associations. Facies were interpreted based on lithology, sedimentary structures, texture, bedding, fossils, and trace fossils (Walker, 1984; Bhattacharya & Walker, 1992; Walker & Plint, 1992; Allen & Posamentier, 1994; Kamola & Van Wagoner, 1995; Yoshida, 2000; Pemberton, 1992). Sections were measured along the footwall of the Indio Normal fault that exhumes the lower thrust plate (Fig. 1.3). Environments were inferred from facies associations that together provided information about processes and fauna. The outcrops were correlated through walking of contacts as well as the use of high-resolution photographs from Google Earth and the U.S. National Map. These images also provided sections of facies geometries and how thickness changes were accommodated between sections, including recognition of growth-strata relationships.

The sequence stratigraphic model of the Cox sandstone is based on correlation of 8 closely spaced (0.5 km to 1 km) measured outcrop sections with a cumulative 1465m thickness (Fig.1.3). In this study, we basically considered stacking trends and patterns, stratal geometries,

chronostratigraphic surfaces and substrate controlled ichnofacies to delineate the sequence stratigraphic surfaces, system tracts and stratigraphic sequences (Posamentier & Vail, 1988; Van Wagoner *et al.*, 1988, 1990; Taylor & Lovell, 1995; Kamola & Van Wagoner, 1995; O'Byrne & Flint, 1996; Catuneanu, 2002; Catuneanu *et al.*, 2009).

1.6 Facies Associations and Depositional Environments

Six facies associations were inferred from the Cox Sandstone strata in the Indio Mountains (Table 1). We considered lithology, sedimentary structures, nature of bedding contacts, and distribution of bioturbation to describe the facies associations. These facies associations are used as a guide to aid in the synthesis of a sequence stratigraphic framework of the Cox Sandstone.

1.6.1 FA1: Massive mudstone, limestone, and current and wave ripple facies association

Description

This facies association predominantly consists of greenish gray to purple shale intercalated with subordinate amount of very thin bedded greenish gray siltstone (Fig. 1.4A). Thin beds (10-20 cm) of very fine grained rippled sandstone occur sporadically throughout this facies (Fig. 1.4B). The mud facies is soft and mostly covered. Where it is exposed, the thickness of individual units varies from few meters to ten's of meters (Fig. 1.4A). The massive mudstones lack obvious burrows and primary sedimentary structures, while very fine grained sandstones encapsulated in the mudstones show intense bioturbation, suggesting the mudstones are also bioturbated. Thin limestone beds (10 -50 cm thick) are encased in the mudstone facies, but are rarely exposed, typically being covered. A single fossiliferous limestone was found at about 14 m above the base of one interval of this facies that contains turitella and several benthic foraminifera (Fig. 1.4C). The upper two-thirds of the limestone consist of about 4m thick, bluish gray fossiliferous limestone which crops out throughout the Indio Mountains region (Figs 1.4D and 1.4E). Due to poor preservation species could not be identified. Mount (1960) reported

fragments of Exogyra sp. in similar intervals and Underwood (1975) found *Exogyra texana*, Gryphea *washitaensis*, *Toucasia* sp.

Interpretation

The thick mudstone intervals with very fine grained sandstone and siltstone, parallel lamination, and current and wave ripples, and marine fossils support an interpretation of an inner shelf environment. The presence of fossil assemblages described above indicates an open marine environment. Albritton & Smith (1965) also noted the similar marine gastropods and pelecypods fossils in all sections in the northern part of Quitman Mountains and in upper part of the southern Quitman Mountains. The deposition of mudstone indicates long period of quiescent environment (Howard & Reineck, 1981).

1.6.2 FA 2: HUMMOCKY CROSS STRATIFIED SANDSTONE AND LAMINATED SANDSTONE FACIES ASSOCIATION

This facies association mostly consists of fine grained, well sorted, white sandstone with hummocky cross stratification (HCS), parallel sub-horizontal lamination, and wave ripples (Figs 1.5A, B and C). Individual sandstone beds range from few centimetre to a meter or two with general coarsening upward trend. Sandstone beds include scattered very thin beds of greenish gray siltstone. Scattered pebbles and granules, mud chip clasts are common at the base and/or within the facies. *Planolite, Paleophycus, Arenicolite, Diplocaterion, Thalassinoides* are common trace fossils found in this association (Fig. 1.5D).

Interpretation

The existence of Hummocky Cross Stratification indicates storm-waves in an environment that is normally below fair-weather wave base (Walker, 1984). The presence of laminated sandstone signifies the influence of wave working in storm conditions (Howard and Reineck, 1981). Thin wave-rippled beds in the lower part of the facies indicate oscillatory currents (Fig. 1.5C). Scattered pebbles and granules in the fine grained sandstone are interpreted as having moved onto the lower shoreface during the storm and left behind as a post-storm lag (Clifton, 2006). The occurrence of *Cruziana* Ichnofacies (Fig. 1.5D) suggests a shallow marine