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Deciphering the impact of sea-level changes and tectonic movement on erosional sequence boundaries in carbonate successions: A case study from Tertiary strata on Grand Cayman and Cayman Brac, British West Indies

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ABSTRACT

The stratigraphic architecture of carbonate successions that develop on geographically isolated islands reflects the balance between sea-level highstands, lowstands, and tectonic activity. This is readily apparent in the Tertiary carbonate sequences on the Cayman Islands that are formed of the Bluff Group, which includes the Brac Formation (Lower Oligocene), Cayman Formation (Middle Miocene), and Pedro Castle Formation (Middle Pliocene). These strata are overlain by the Pleistocene Ironshore Formation. The unconformities that define the boundaries between these formations are variable because some developed during one cycle of past erosion, others developed through two or more past erosional cycles, and some are still developing today. Some unconformities, like the one at the top of the Cayman Formation, are geographically variable because they underwent different developmental histories in different areas. The challenge with architectural complex successions, like those on the Cayman Islands, is that of deciphering the impact of sea-level changes as opposed to tectonic influences.

During sea-level lowstands, the older carbonate successions were exposed on land and modified by surface and subsurface karst development. At the same time, marine erosional processes affected the coastal areas. Surface karst modification, which commonly produced rugged topographies with erosional relief at least 62 m, was controlled largely by rainfall, runoff, and stratal dip. Weathering on Grand Cayman at the end of the Miocene, for example, produced a dish-shaped topography with elevated peripheral rims. In contrast, uplift of the east end of Cayman Brac between the Late Pliocene (3.6 Ma) and ~400 ka, elevated the basal part of the Cayman Formation 33 m above sea level. Subsequent karst development, which is still ongoing today, removed most of the Cayman Formation on the eastern part of the island and produced peripheral rims that are higher than those on Grand Cayman. During some lowstands, like that between the Late Pliocene and ~400 ka, coeval coastal erosion led to the development of coastal benches that cut into the older carbonate strata. The combination of karst development in the islands' interiors and coastal erosion produced complex, rugged topographies that strongly influenced patterns of deposition during the following highstand. The complex stratigraphic architecture of the carbonate successions on the Cayman Islands reflects the variable impact of tectonics, karst development, and coastal erosion that was associated with each lowstand–highstand cycle.

1. Introduction

The stratigraphic architecture of carbonate successions on isolated oceanic islands reflects the balance between deposition that takes place during sea-level highstands and erosion that takes place during sea-level lowstands (Choquette and James, 1988; Esteban, 1991; Mylroie and Carew, 1995). Thus, the three-dimensional geometry of a formation on such islands is controlled, to a large extent, by the topographies of the bounding unconformities. This is especially true if the relief on those unconformities is high when compared to the thickness of the formation. Although a variety of factors, such as the duration of exposure, climate, bedrock type, paleohydrology, paleotopography, and vegetation, may affect the development of an unconformity (Wright, 1982, 1996; Esteban and Klappa, 1983; Saller et al., 1994, 1999; Wright and Smart, 1994; Budd et al., 2002; Weidlich, 2010), it has long been recognized that eustatic changes in sea level and tectonic movements are the key factors in their development (Choquette and James, 1988). Identifying the impact of eustasy as opposed to tectonism on unconformity development is, however, commonly problematic

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because both processes can produce exactly the same effects (Choquette and James, 1988; Budd et al., 1995; Dickinson et al., 2002).

Grand Cayman and Cayman Brac, British West Indies are ideal for examining this issue. Within 150 km of each other (Fig. 1), these isolated islands have experienced the same eustatic changes, climate, and depositional conditions from the Oligocene to present. Grand Cayman and Cayman Brac are, however, located on different fault blocks that have different tectonic histories (Horsfield, 1975; Stoddart, 1980; Jones and Hunter, 1990; Vézina et al., 1999; Coyne et al., 2007). Grand Cayman, with flat-lying strata, is a low-lying island that appears to have experienced little, if any, tectonic movement. In contrast, Cayman Brac, which rises up to 46 m above sea level (asl) at its east end, with the strata dipping gently to the southwest, has been tectonically tilted. By comparing the stratigraphic architectures of these two islands, the impact of tectonics can be separated from the impacts of eustasy on the development of the unconformities found in the Oligocene to Pleistocene successions. Thus, this paper (1) delineates the topography of each unconformity on Grand Cayman and Cayman Brac, (2) compares the topographic features of each unconformity on each island, (3) illustrates the stratigraphic architectures dictated primarily by eustatic sea-level changes, and (4) identifies the influences of local tectonic activity on subaerially-formed unconformities.

2. Methods

The present-day topographies of Grand Cayman and Cayman Brac are illustrated by using digital elevation models (DEMs) developed from data provided by the Lands and Survey Department, Government of the Cayman Islands. The DEM, with a grid resolution of 3 m, used the Universal Transverse Mercator (UTM) projection system and the North American Datum of 1927. The elevation information, including the heights and profile graphs, were obtained through spatial analyst tools provided in ArcGIS 10 software.

Over the last 30 years, 97 wells on Grand Cayman and 15 wells on Cayman Brac have been drilled and sampled. On Grand Cayman, these wells yielded cores (54 wells), a mixture of cores and well cuttings (8 wells), or well cuttings (35 wells) with each sample being collected over an interval of 0.8 m. On Cayman Brac, well cuttings (15 wells) collected over 0.8 m intervals are the only samples available. Collectively, these samples, accompanied with outcrops, allow analysis of the sequences and delineation of the unconformities between different formations. The spatial architectures of these unconformities were interpolated from the scattered wells and outcrops by using the kriging method, according to a spherical semi-variogram model. This procedure was done by the 3D Surface extension of Surfer 10 software.

3. Geologic setting

Grand Cayman and Cayman Brac are located on the Cayman Ridge (Jones, 1994; Vézina et al., 1999), which parallels the Oriente Transform Fault that separates the Caribbean Plate from the North American Plate (Perfit and Heezen, 1978; Fig. 1). The Oriente Transform Fault extends eastward from the north end of the Mid-Cayman Rise, which is an active spreading center, whereas the Swan Island Transform Fault extends westward from the south end of the Mid-Cayman Rise (MacDonald and Holcombe, 1978). The Cayman Trench (Fig. 1B), with its northern margin defined by the Oriente Transform Fault, is a pull-apart basin, with the depths up to 7686 m.

Between the Late Eocene and Oligocene, the Oriente Transform Fault detached Grand Cayman and Cayman Brac from their parent arc and transported them to their present locations (Iturralde-Vinent, 1994; Calais and Mercier de Lépinay, 1995). Since the early Middle Miocene, localized extensional features began to form (Iturralde-Vinent and Macphee, 1999; Iturralde-Vinent, 2006), resulting in Cayman Brac being on a different fault block than Grand Cayman (Matley, 1926; Horsfield, 1975; Stoddart, 1980; Vézina et al., 1999). After the Late Miocene (7.25 Ma using the time scale of Gradstein et al., 2012, their Fig. 1.2), Cayman Brac experienced tectonic tilting until about 125 ka, whereas Grand Cayman appears to have remained tectonically stable (Jones and Hunter, 1990; Vézina et al., 1999; Zhao and Jones, 2012a, 2013).

Matley (1926) originally assigned the Tertiary strata of the Cayman Islands to the Bluff Limestone. Jones et al. (1994a, 1994b) subsequently renamed the succession as the Bluff Group with the constituent formations being the unconformity bounded Brac Formation (Lower Oligocene), Cayman Formation (Middle Miocene), and Pedro Castle Formation (Pliocene). The Ironshore Formation (Pleistocene) unconformably overlies the Bluff Group (Fig. 2). The Brac Formation, exposed only on Cayman Brac, is formed of limestones that are locally replaced by coarsely crystalline, fabric-destructive dolomite (Jones and Hunter, 1994a; Uzelman, 2009; Zhao and Jones, 2012b). The bioclastic wackestones to grainstones included numerous large *Lepidocyclina* along with fewer small foraminifera, red algae, echinoid plates, gastropods, and bivalves but only scattered corals (*Porites*). Jones and Hunter (1994a) suggested that these facies developed in low to moderate energy conditions on a shallow carbonate bank. The Cayman Formation is formed largely of finely crystalline, fabric retentive

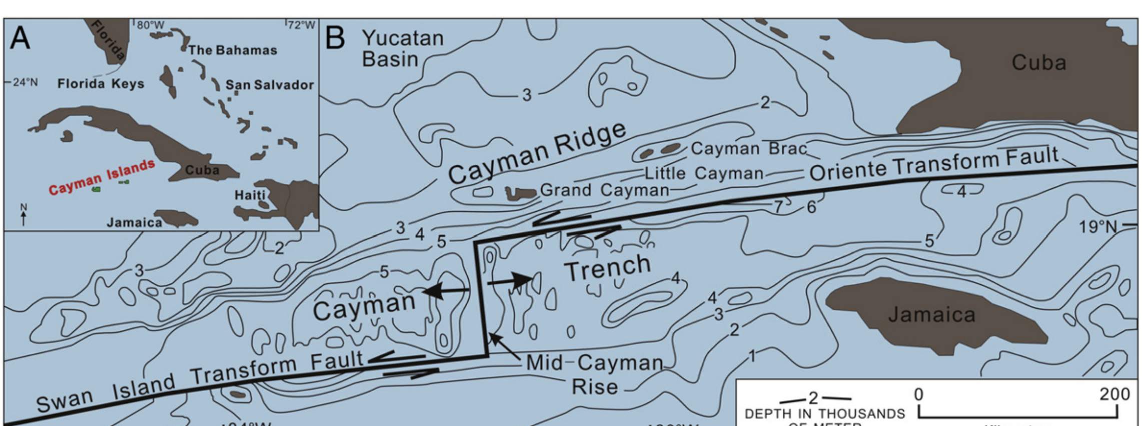

Fig. 1. (A) Location of Cayman Islands; (B) Locations of Grand Cayman and Cayman Brac relative to the Mid-Cayman Rise, the Cayman Trench, and the Oriente Transform Fault (modified from Jones, 1994, and based on maps from Perfit and Heezen, 1978, and MacDonald and Holcombe, 1978).