STRUCTURAL ANALYSIS OF THE SAN MARCOS ARCH

by

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ABSTRACT

The San Marcos Arch is a subsurface feature of Central Texas that is thought to have been an active high during portions of the Cretaceous, affecting the depositional patterns of the sediments deposited during that period. While typically referred to as the San Marcos Arch, some articles refer to the same structure as the San Marcos Platform, indicating a structure with no apex. Understanding the structure of the San Marcos Arch/Platform and identifying its location in the subsurface is significant for exploration geologists operating in Central Texas. Among the affected strata is the Eagle Ford Group, a mudrock known for its abundant hydrocarbon content that is a major unconventional reservoir. Thinning of the Eagle Ford over the top of the San Marcos Arch has been observed for many years and directly affects hydrocarbon exploration in the area. To better understand the nature of the structural feature, formation tops were used to build isopach and structure maps for Cretaceous strata including the Eagle Ford Shale, the Buda Limestone, and the Del Rio Shale; these tops were picked on raster well logs. From these methods it is interpreted that "San Marcos Platform" may be a more accurate name for the Central Texas structure.

Introduction

The Eagle Ford Shale in South Texas has been a significant unconventional source of oil and gas since its discovery in 2008 and currently produces 773,306 barrels of oil per day (Texas Railroad Commission, 2020). Its deposition was affected by the San Marcos structure, which we observe as thinning of the Eagle Ford over the top of the structure. As such, a thorough understanding of the San Marcos Arch or Platform would benefit exploration geologists operating in Central Texas.

Locations of the San Marcos Arch/Platform is placed in different locations by various authors, although they nearly always include Fayette, Bastrop, Caldwell, and Gonzales counties. The possibility of stratigraphic traps created by the presence of the San Marcos Arch or Platform was explored by Rives (1963), who believed the arch to be a positive structural feature favorable to the formation of carbonates with the possibility of clastic stratigraphic traps. A year prior, Tucker (1962) described the San Marcos structure as "…a very broad, somewhat undulating, gentle anticlinal nose or platform which extends southeastward from the Llano Uplift…The Maverick and East Texas basins form, respectively, its southwestern and northeastern boundaries." Other papers, such as Winter (1961), refer to the structure as the San Marcos Platform. The intention of this paper is to:

1) Determine how the San Marcos Arch or Platform affects Cretaceous strata in Central Texas at the southern extent of the structure.
2) Provide evidence using well log data to determine if the structure typically known as the San Marcos Arch is a platform or an arch at the structure's southern extent.

Regional Geology

Structural Background

The Llano Uplift contains the oldest rocks in Texas and can be considered an appropriate "starting point" when discussing Central Texas geology. The Grenville Orogeny was a mountain-building event resulting from the collision of Amazonia and Baltica with the southern margin of Laurentia (present-day Texas and Mexico) approximately 990 million years ago (Cawood and Pisarevsky, 2017; Fig. 1). Metasedimentary and metamorphic rocks originally formed due to the Grenville Orogeny approximately 1.2 billion years ago now form the structural dome known as the Llano Uplift. Erosion of younger Paleozoic and Cretaceous rocks created an erosional window for features such as Enchanted Rock.

The supercontinent Pangaea began to split about 200 million years ago during the Late Triassic/Early Jurassic. This separation continued into the Late Jurassic and created a rift that is now the Gulf of Mexico, while simultaneously moving the Yucatan block away from the North American Plate. Hypersaline shallow ocean waters periodically covered the new Gulf of Mexico Basin, leading to salt deposits in the Middle Jurassic (Salvador, 1991). Salt deposition during this time affects hydrocarbon exploration in East Texas/West Louisiana as well as Northern Mexico.

The Cretaceous Period was a time of high eustatic sea-level. Global ocean anoxic events (OAEs) also characterize the Cretaceous (Phelps, 2015). Cretaceous seas created the Western Interior Seaway that connected the Arctic Ocean with the Gulf of Mexico and covered most of Texas (Fig. 2). It is under these conditions that the Eagle Ford Shale was deposited throughout Texas. Structures such as the Sabine Uplift in East Texas and the San Marcos Arch/Platform in Central Texas, however, affected deposition in such a way as to create various facies within the Eagle Ford Group. The Harris Delta complex, carrying sediments from the Ouachita and Sabine

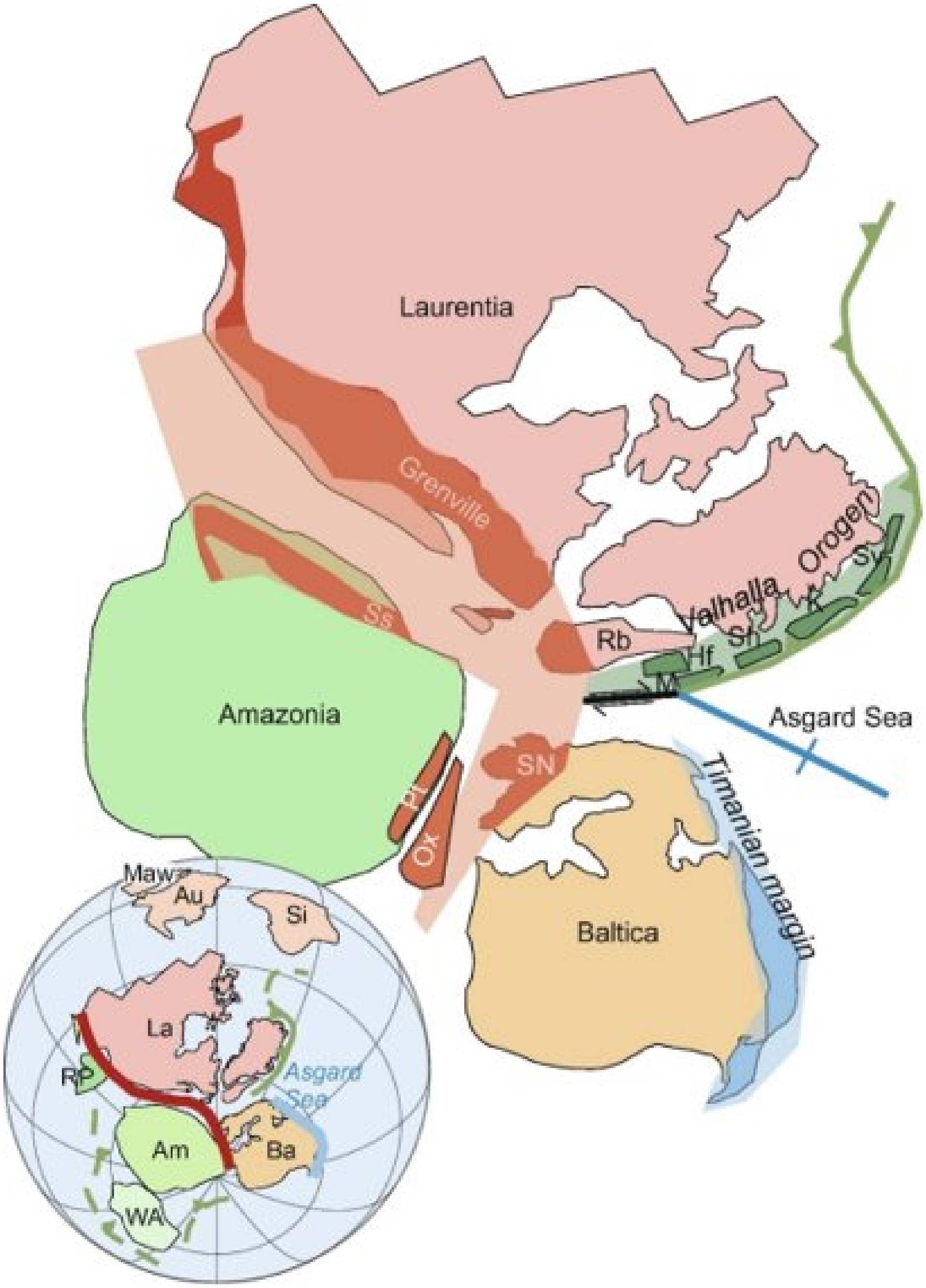

Figure 1. Grenville Orogeny (990 ma). The collision of Amazonia and Baltica with the southern margin of Laurentia (present-day Texas and Mexico) creates the supercontinent Rodinia. From Cawood and Pisarevsky, (2017).

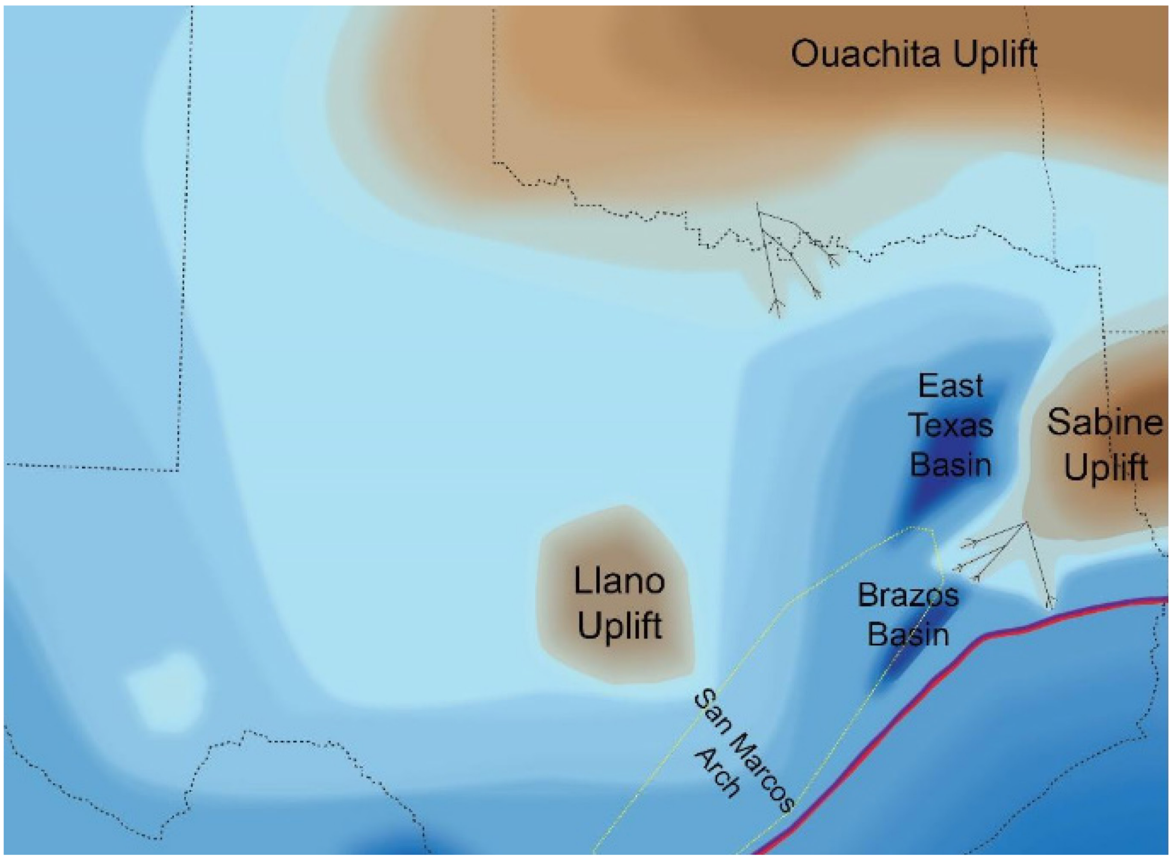

Figure 2. The Western Interior Seaway covers most of Texas, depositing the Eagle Ford Shale. From Denne and Breyer, (2016).

Uplifts, produced clay-rich intervals within the Eagle Ford that make up the rock record north-east of the San Marcos Arch/Platform, whereas the Eagle Ford south-west of the Arch/Platform is more calcareous. Predictably, the Eagle Ford had a higher rock accumulation rate north-east of the San Marcos Arch/Platform as there was a much higher supply of sediments (Denne and Breyer, 2016).

One of the earliest summaries of the San Marcos structure's geologic history was Fowler (1956) who claimed the structure was an arch with an axis roughly coinciding with the Guadalupe-Caldwell County line (Fig. 3). A year later, Zink (1957) saw the structure much like Fowler; Zink also showed a 533% fluctuation in thickness of the Del Rio Formation from the Rio Grande Embayment to the San Marcos Arch (176 feet in western Zavala County to 33 feet in Gonzales County, Fig. 4).

Winter (1961), however, supported the term "platform" for the structure, saying "The term platform is preferred, however, because of its depositional topography. The formations thicken at an extremely small and constant rate (on the order of 1 to 2 feet per mile for most formations) in this province…" Winter also claimed that the structure was a marine topographic high prior to deposition of the Del Rio Shale.

Tucker (1962) referred to the San Marcos structure as "…a very broad, somewhat undulating, gentle anticlinal nose or platform which extends southeastward from the Llano Uplift…The Maverick and East Texas basins form, respectively, its southwestern and northeastern boundaries." Tucker also published isopach maps of Cretaceous strata and gave stratigraphic descriptions of formations that are used for analysis later in this paper. Rives (1963) explored the possibility of stratigraphic traps due to thinning of carbonates along the structurally positive San Marcos Arch. Rives describes the structure as a monocline plunging southeastward

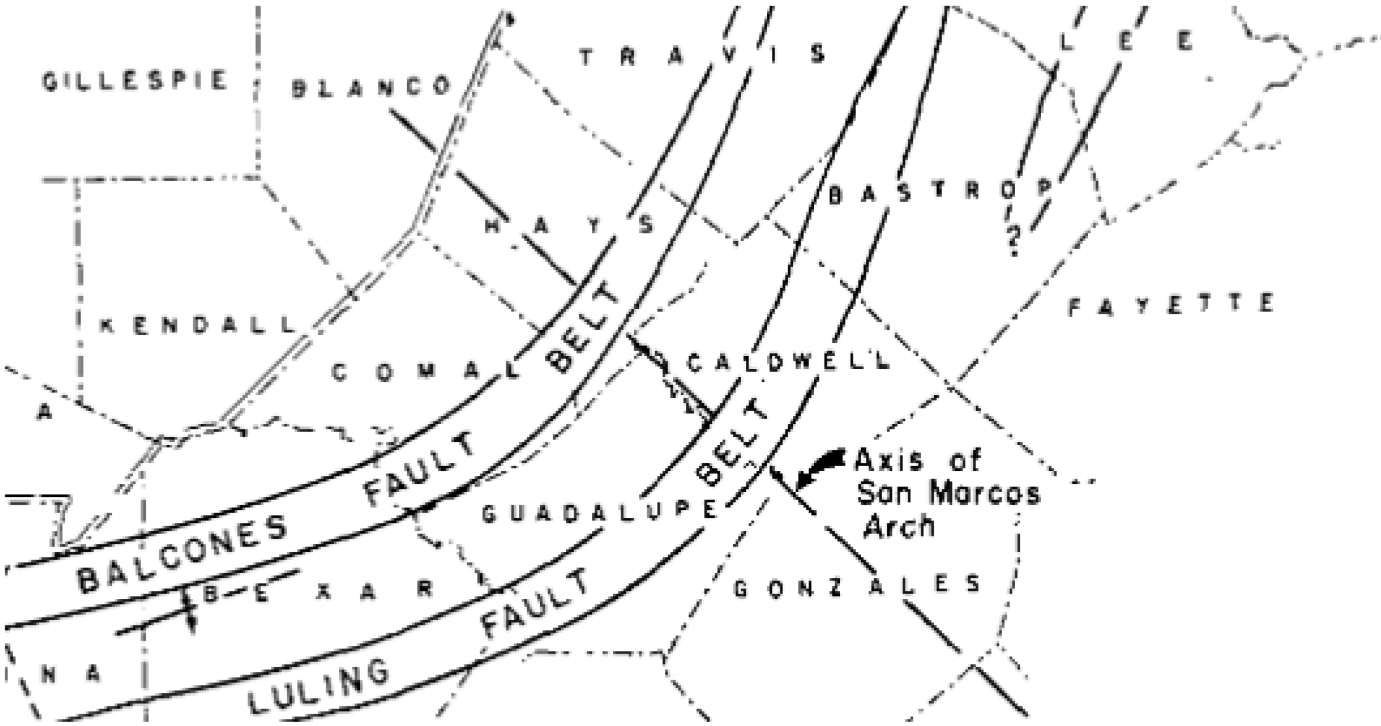

Figure 3. Map of central Texas structures. Modified from Fowler, (1956).

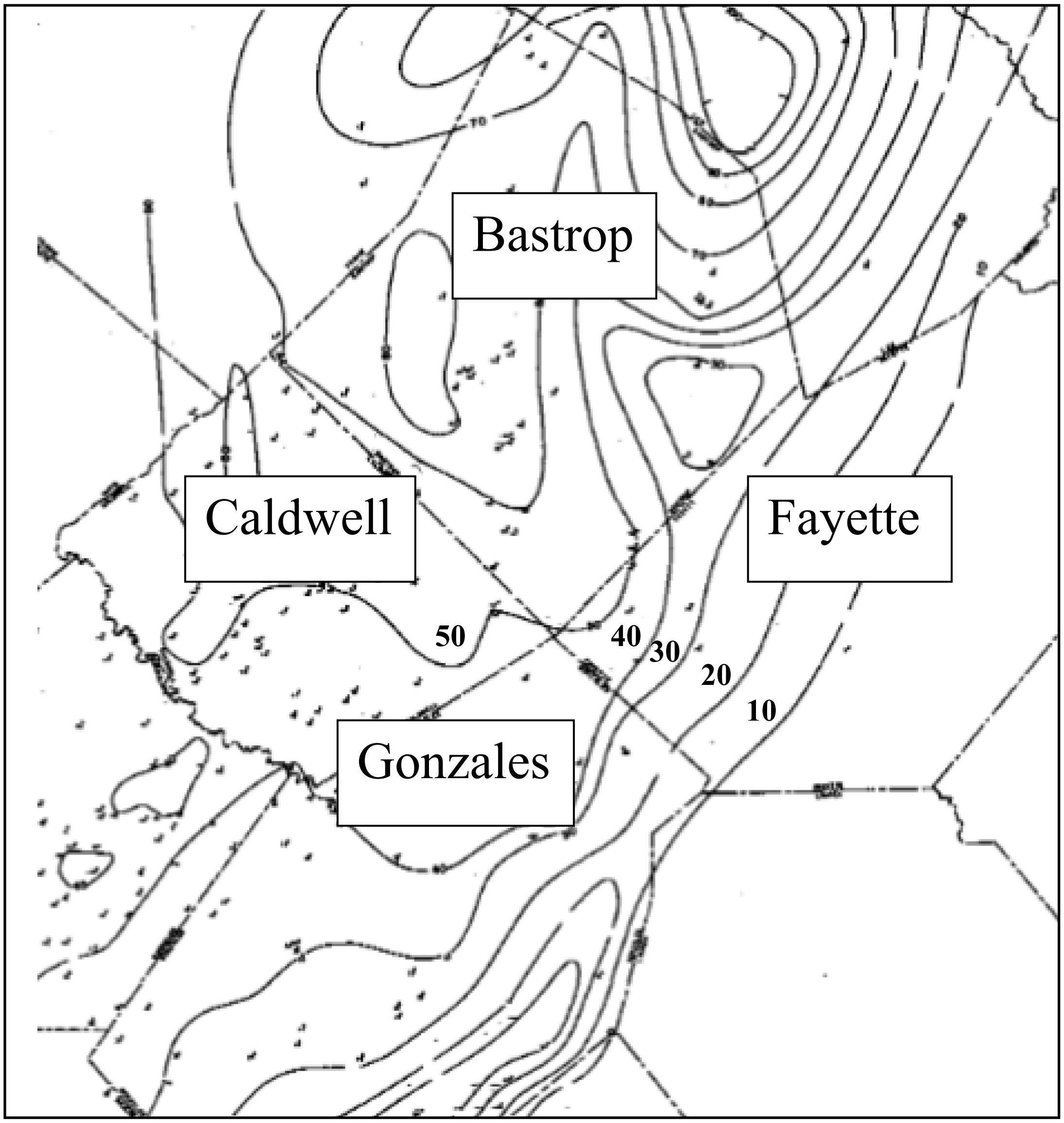

Figure 4. Isopach map of the Del Rio Shale. Contour interval = 10 feet.
Modified from Tucker, (1962).

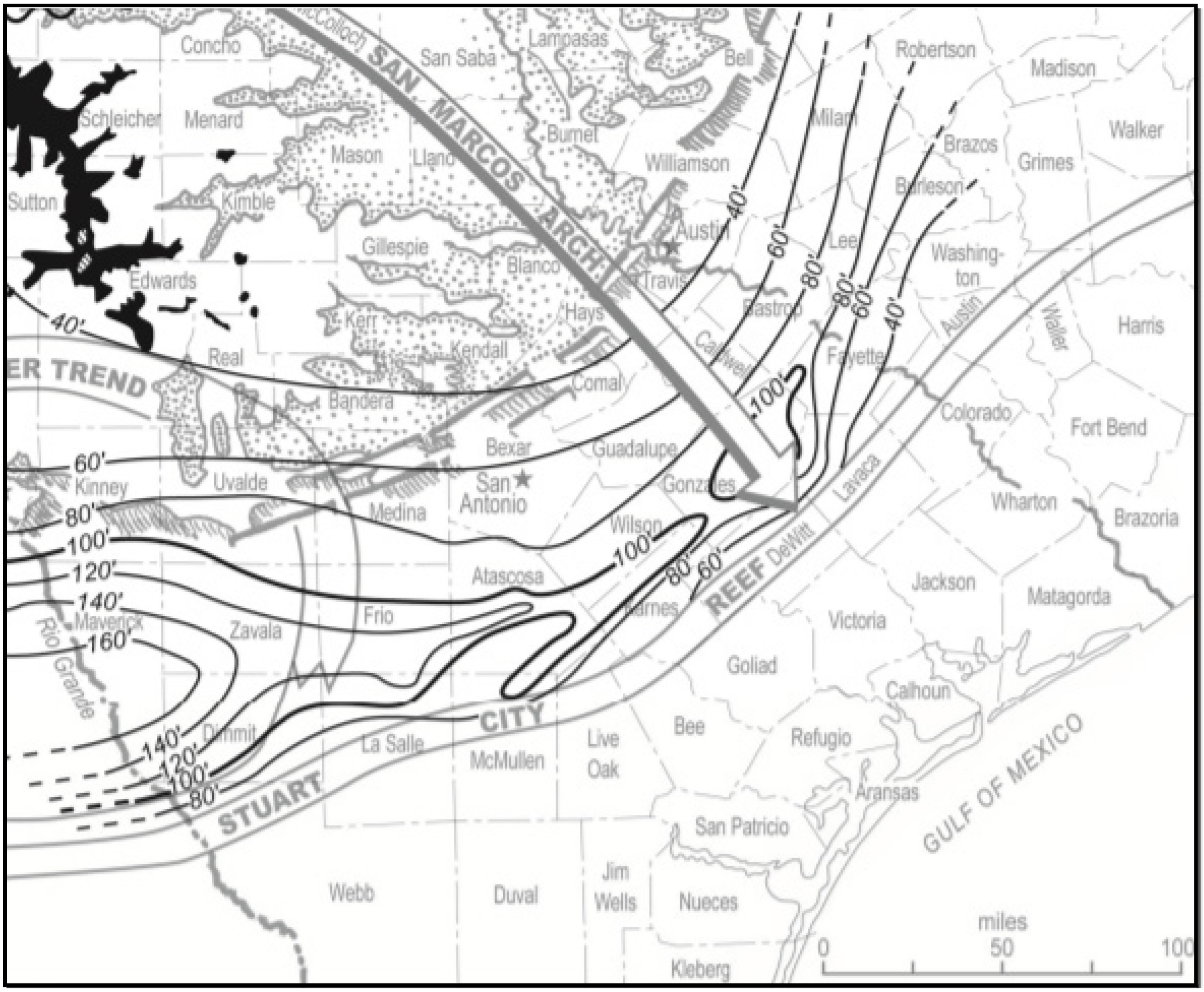

Figure 5. Isopach map of the Buda Limestone. Contour interval = 20 feet.
Modified from Rose, (2016).

towards the Stuart Reef Complex and probably terminating at the Sample fault system, whereas Rose (2016) describes it as the axis of the Central Texas Platform (Fig. 5).

The San Marcos structure has moved throughout time and creates complex paleotopography in present-day central Texas (Laubach, 1990). During the Lower Cretaceous, the San Marcos structure was not a northwest-trending positive arch as it is today in the subsurface. Angular unconformities and thinning of Late Cretaceous strata indicate that the San Marcos Arch/Platform was present during the Late Cretaceous and early Tertiary.

Porter (2017) recognized both a San Marcos Arch and a San Marcos Platform. In her case, the San Marcos Arch extends from northwest of the Llano Uplift in Nolan County to southeast of the Uplift to the Travis-Bastrop County border (roughly the northern border of this project's study area). Porter shows the Platform extended well outside of central Texas (Fig. 6).

Three possible explanations for the presence of the San Marcos structure were presented by Laubach (1990): deep-seated plutons, buoyant crustal blocks, and Mesozoic-Cenozoic orogenesis. Doming over plutons does cause deformation in the form of arches; however, the San Marcos structure is "…elongate rather than equant and lack[s] the short wavelength, positive gravity and magnetic anomalies and steep flanks that characterize small intrusions in the gulf." Arches can also be formed from isostatic rise or subsidence of crustal blocks such as lower-density terranes accreted on during Paleozoic continental collision. However, differential subsidence should produce persistent thinning of Cretaceous strata rather than the angular unconformities we find along the San Marcos structure. Laubach's final explanation is Mesozoic-Cenozoic orogenesis. Tectonic activity in present-day Mexico during the middle Mesozoic to early Cenozoic produced northeast-trending tectonic shortening. Orogenesis led to an influx of clastic sediment that produced northwest-trending structural highs. Deformation from orogenesis can cause deformation of the continental interior up to 1000 kilometers from the orogenic front. Vertical and lateral sediment loading near the orogenic front could have produced the stresses required to create a structure like the San Marcos structure (Laubach, 1990).

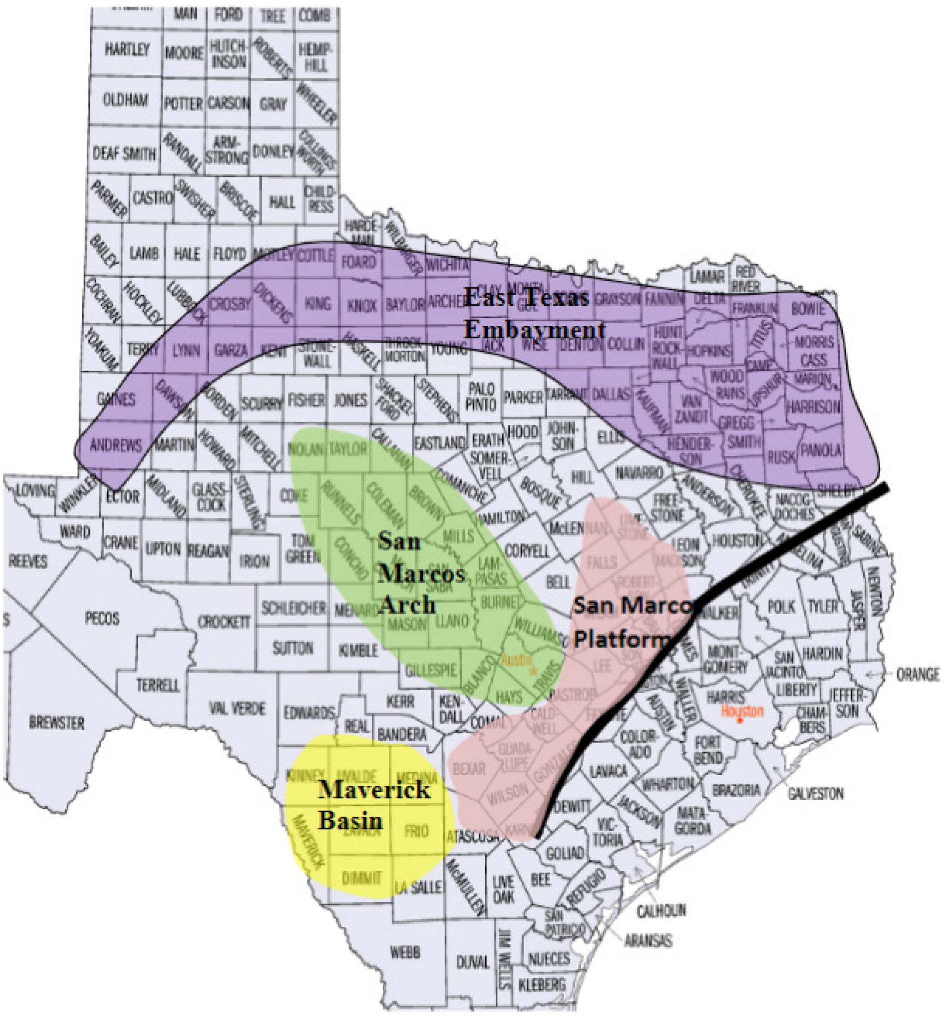

Figure 6. Porter's interpretation of both a San Marcos Arch and a San Marcos Platform. Modified from Porter, (2017).

Upper Albian - Santonian Stratigraphy

The Albian-aged Georgetown Limestone has a fairly uniform lithology in the study area, where it is a brown argillaceous limestone deposited in a lower-energy environment than the underlying Edwards Limestone. The Georgetown Limestone has similar low gamma ray values to both the Austin Chalk and the Buda Limestone (Fig. 7). Winter (1961) divided the Georgetown deposited on the San Marcos structure into upper and lower members and suggested the change in energy of the depositional environments between the Georgetown and Edwards could indicate uplift of the San Marcos structure.

The Lower Cenomanian Del Rio Shale rests unconformably underneath the Buda Limestone. It represents a brief influx of clays deposited on top of the carbonate setting of Buda time. The Del Rio reaches thickness of more than 300 feet (91.4 meters) in the Maverick Basin (Rose, 2016).

The Lower Cenomanian Buda Limestone unconformably underlies the Eagle Ford Shale when the Maness Shale is not present and displays low-gamma ray values. It is a light tan, hard, and dense limestone (Zink, 1957). There is a gradational contact between the Buda Limestone and the Maness Shale whenever the Maness is present (Denne and Breyer, 2016).

The Lower Cenomanian Maness Shale is an argillaceous mudrock that is sometimes treated as the basal member of the Eagle Ford. The Maness pinches out in the vicinity of the San Marcos structure. A thin uranium-rich phosphatic lag is present where the basin was lacking the clay-dominated siliclastic sediments that formed the Maness. This lag is interpreted as a condensed section (Denne and Breyer, 2016).

The Eagle Ford Shale is divided into two units, based primarily on its gamma ray signature related to its TOC content. The Middle to lower Upper Cenomanian Lower Eagle Ford generally contains more TOC and thus has higher gamma ray values than the upper Upper Cenomanian to Upper Turonian Upper Eagle Ford. In South Texas the Lower Eagle Ford consists of organic-rich marls and gradually thins from 47 meters (154.2 feet) south of the San Marcos structure to approximately 20 feet (6.1 meters) on top of the structure (Denne and Breyer, 2016). Near the San Marcos structure the Lower Eagle Ford also contains a clay wedge that Denne and Breyer (2016) postulated was sourced from the Harris Deltas to the northeast; this wedge is sometimes termed the Middle Eagle Ford. The Upper Eagle Ford consists of interbedded limestones and marls, and is marked by an upwards decrease in gamma ray values due to its lower TOC content (Denne and Breyer, 2016). South of the structure, Denne and Breyer (2016) also discovered that facies changes within the Eagle Ford were related to the distance from these East Texas deltaic systems.

The Coniacian-Santonian Austin Chalk is a light-colored, bioturbated chalk. It was deposited in an oxygenated shelf environment (Grabowski, 1984). According to Corbett et al. (1987), the Austin Chalk is best characterized as a very fine-grained carbonate mud with coarser skeletal fragments (Fig. 7).

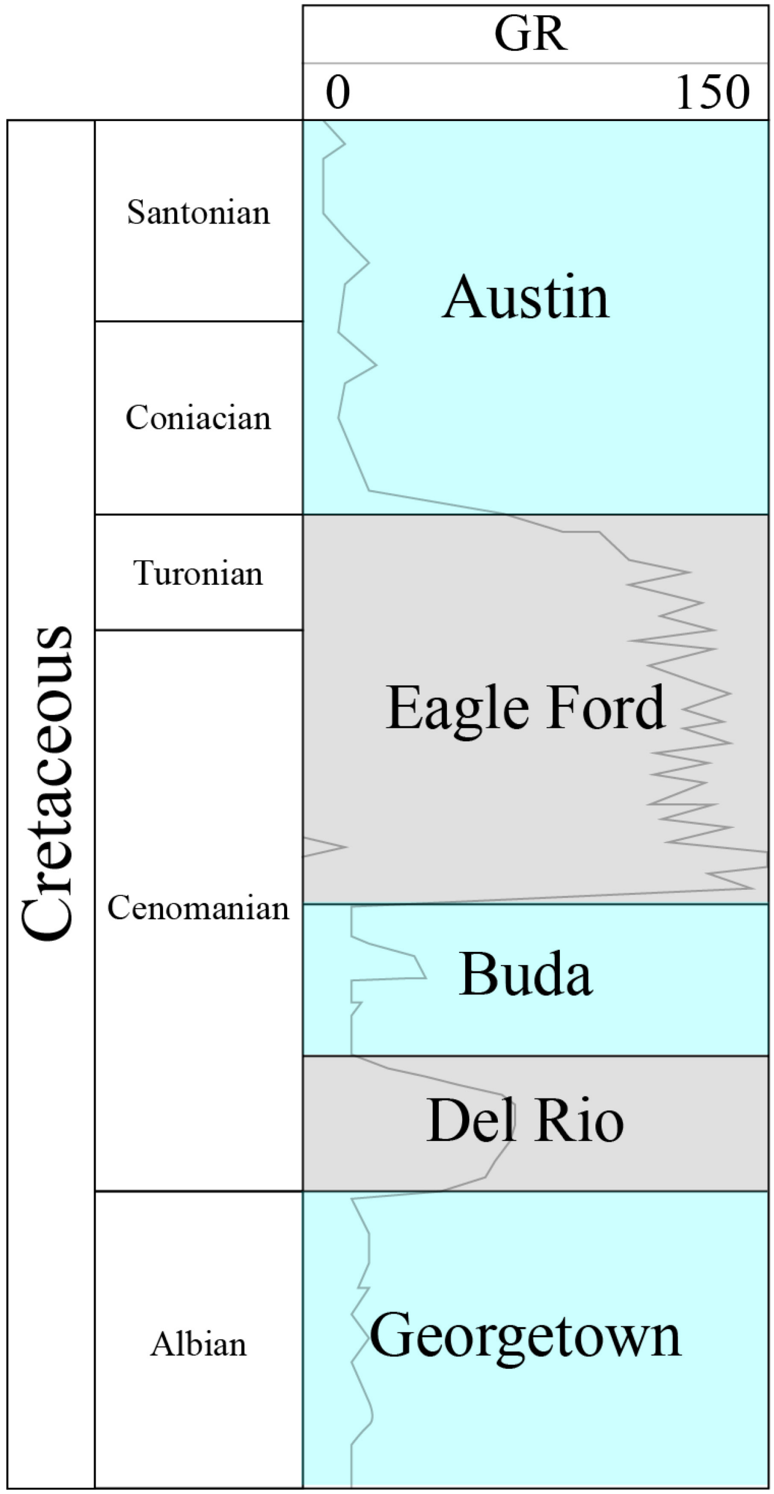

Figure 7. Chronostratigraphic column of the Mid-Late Cretaceous in central-Texas with a typical gamma ray log response for the study area.

Methods

The existence of a structural high should have observable effects in syndepositional strata. In areas affected by a structural high, rock units should thin towards and over the top of a positive structure. Isopach maps were constructed to show these effects. Isopach values were also used for analysis of possible post-depositional movement due to salt tectonics. To examine Cretaceous strata, data from 99 wells obtained from Enverus (formerly Drillinginfo), the Geological Data Library, and the Balcones Energy Library were analyzed (Fig. 8). Formation tops for the Eagle Ford Shale, the Buda Limestone, the Del Rio Shale, and the Georgetown Limestone were manually picked from raster well logs. The phosphate lag present between the Eagle Ford and the Maness was also picked where it was present.

Raster well log data was interpreted with Petra, a software program that is standard in the upstream oil and gas industry. After depth calibrating the .tiff files of the raster logs, gamma ray, spontaneous potential (SP), and resistivity responses were used to pick tops for the aforementioned formations. After picking tops in the Raster Calibration Module, the Mapping Module was used. Inputting location data (latitude and longitude) for each well allowed them to be plotted on a map. Isopach calculations were done within Petra and these values, as well as formation top depths, were used to create contoured grids in the Mapping Module.

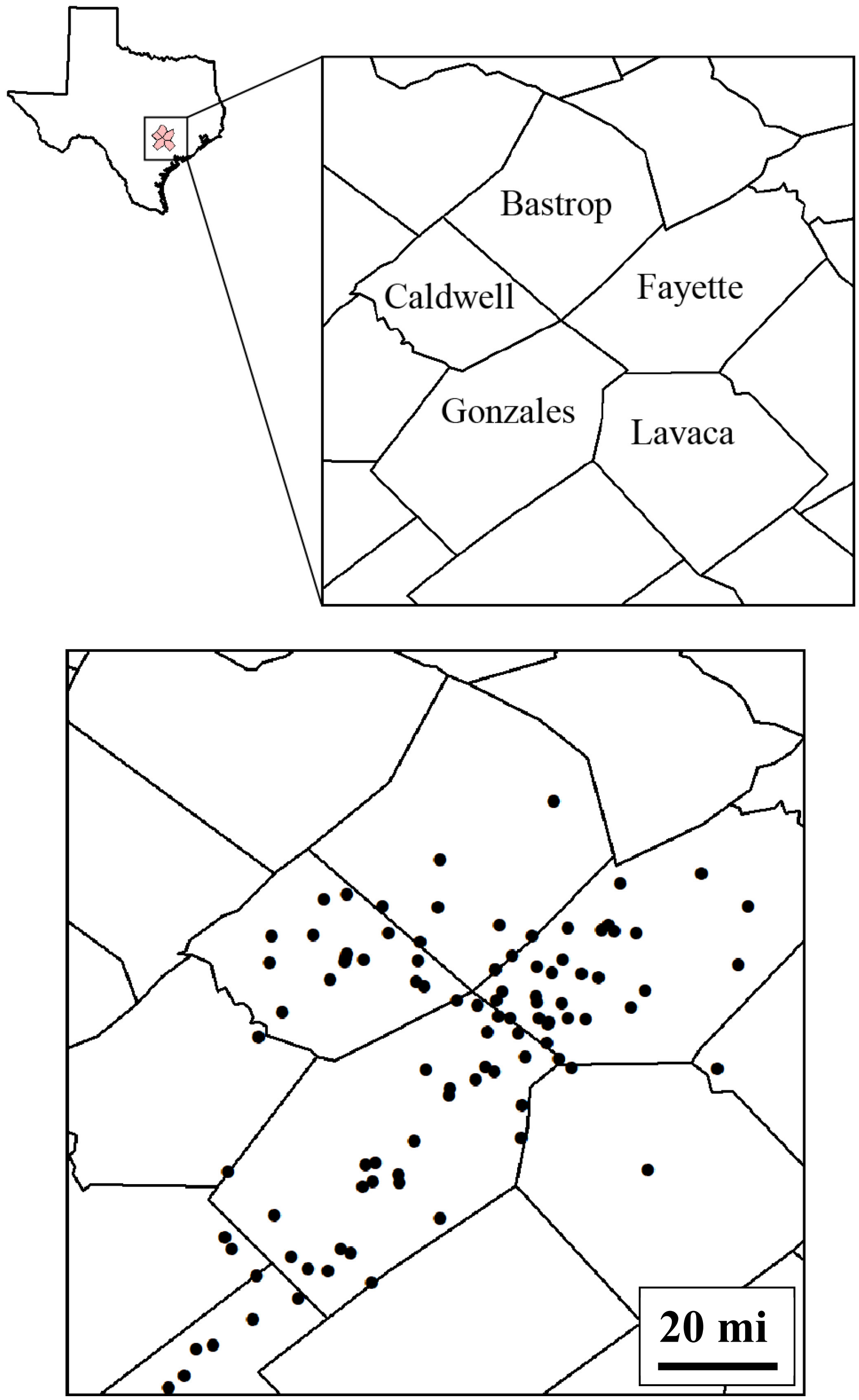

Figure 8. Black dots indicate wells used for the project.

Results

The strike-oriented cross-section of the Del Rio Shale (Fig. 9) shows that it thickens over the southern extent of the San Marcos structure. This is seen between the Fisher and Henderson wells roughly at the Fayette/Gonzales County line and is also seen in the Del Rio isopach map (Fig. 10). The Patillo well in central Gonzales County has a Del Rio thickness of 24 ft (7.3 m) and the Henderson well, roughly on the Fayette/Gonzales County line, has a Del Rio thickness of 55 ft (16.8 m). The Fisher well, located roughly four miles from the Henderson well, has a Del Rio thickness of 39 ft (11.9 m). The Del Rio thins to 35 ft (10.7 m) in the Fleck well located in western Fayette County. The Buda Limestone maintains a relatively constant thickness over the Fayette/Gonzales County line area. The Buda is 92 feet (28 m) thick in the Raymond Neitsch well, 96 ft (29.3 m) thick in the Fisher well, and 86 ft (26.2 m) thick in the Henderson well. In this cross-section, it is thickest in southwestern Gonzales County in the Patillo well (125 ft or 38.1 m) and thinnest in western Fayette County in the Fleck well (73 ft or 22.3 m).

The isopach map (Fig. 10) shows the depositional trend of the Del Rio Shale. Contours follow regional strike in the southwestern extent of the mapped area but deviate around a depositional thick in western Fayette County, which is where the axis of the San Marcos Arch is drawn by many authors.

The cross-sections in figure 11 show the effects of the San Marcos structure on the Eagle Ford Shale. In (a), a cross-section along regional strike shows thinning across the San Marcos structure. The Lessor D well in southwestern Gonzales County has an Eagle Ford thickness of 109 feet (33.2 m). The Eagle Ford gradually thins northeast along strike to 42 feet (12.8 m) in the Raymond Neitsch well and thins to 28 ft (8.5 m) over the San Marcos structure in the Carlos Portales well. In (b), a cross-section along regional dip shows where the structure’s effects may end. Thickness of the Eagle Ford through Caldwell county is relatively constant; the Sharp well has an Eagle Ford thickness of 21 ft (6.4 m), the Wendt well has a thickness of 20 ft (6.1 m), and the Carlos Portales well has a thickness of 28 ft (8.5 m). The Eagle Ford begins to thicken to 45 ft (13.7 m) in the Holland well, eventually becoming 91 ft (27.7 m) thick in the M. Bartos well.

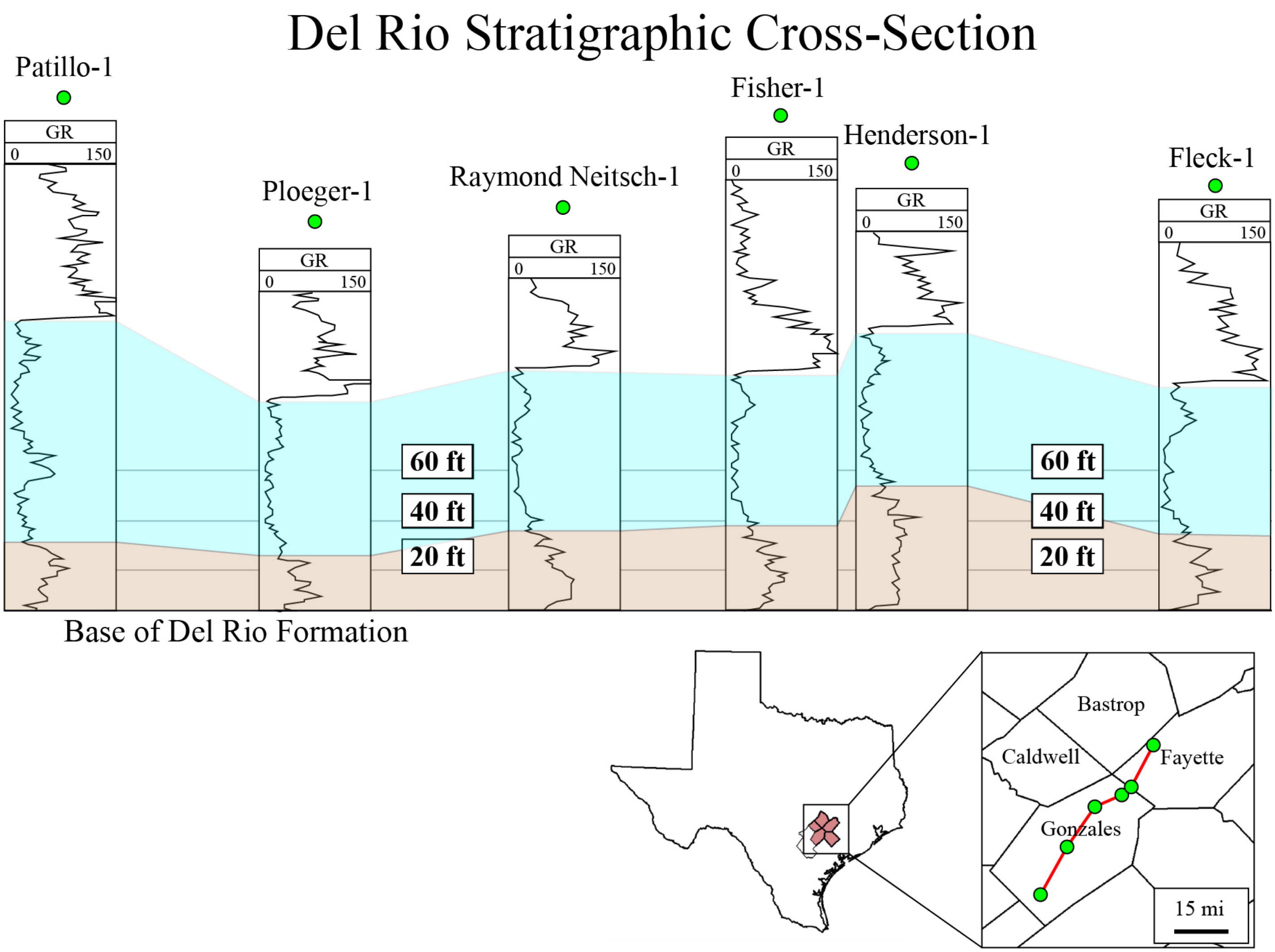

Figure 9. Strike cross-section datumed on the Georgetown Limestone top. Brown shaded portion indicates Del Rio Shale, blue shaded portion indicates Buda Limestone.

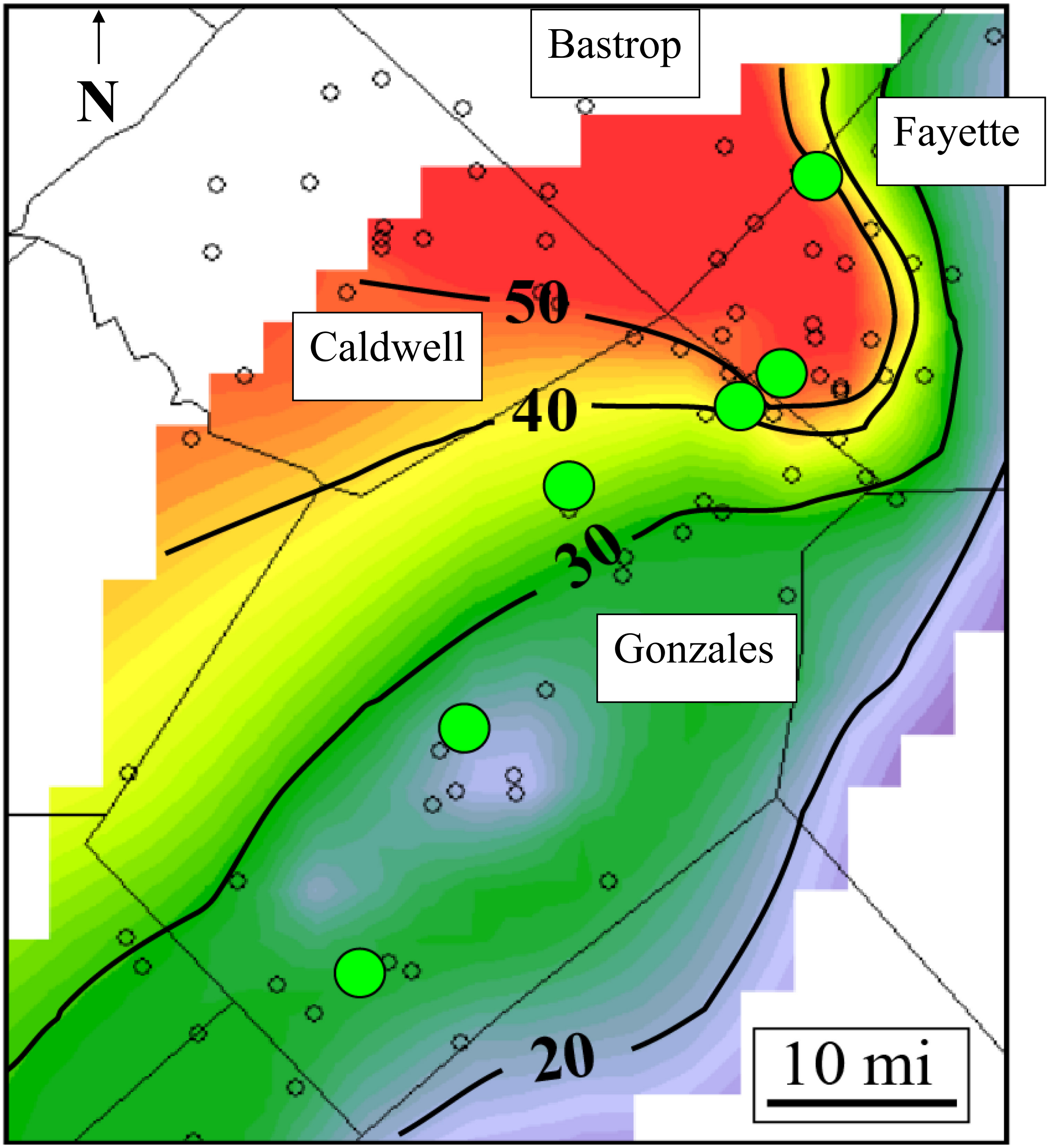

Figure 10. Isopach map of the Del Rio Shale. Contour interval in feet.
Green dots represent wells used in Figure 8 cross-section.

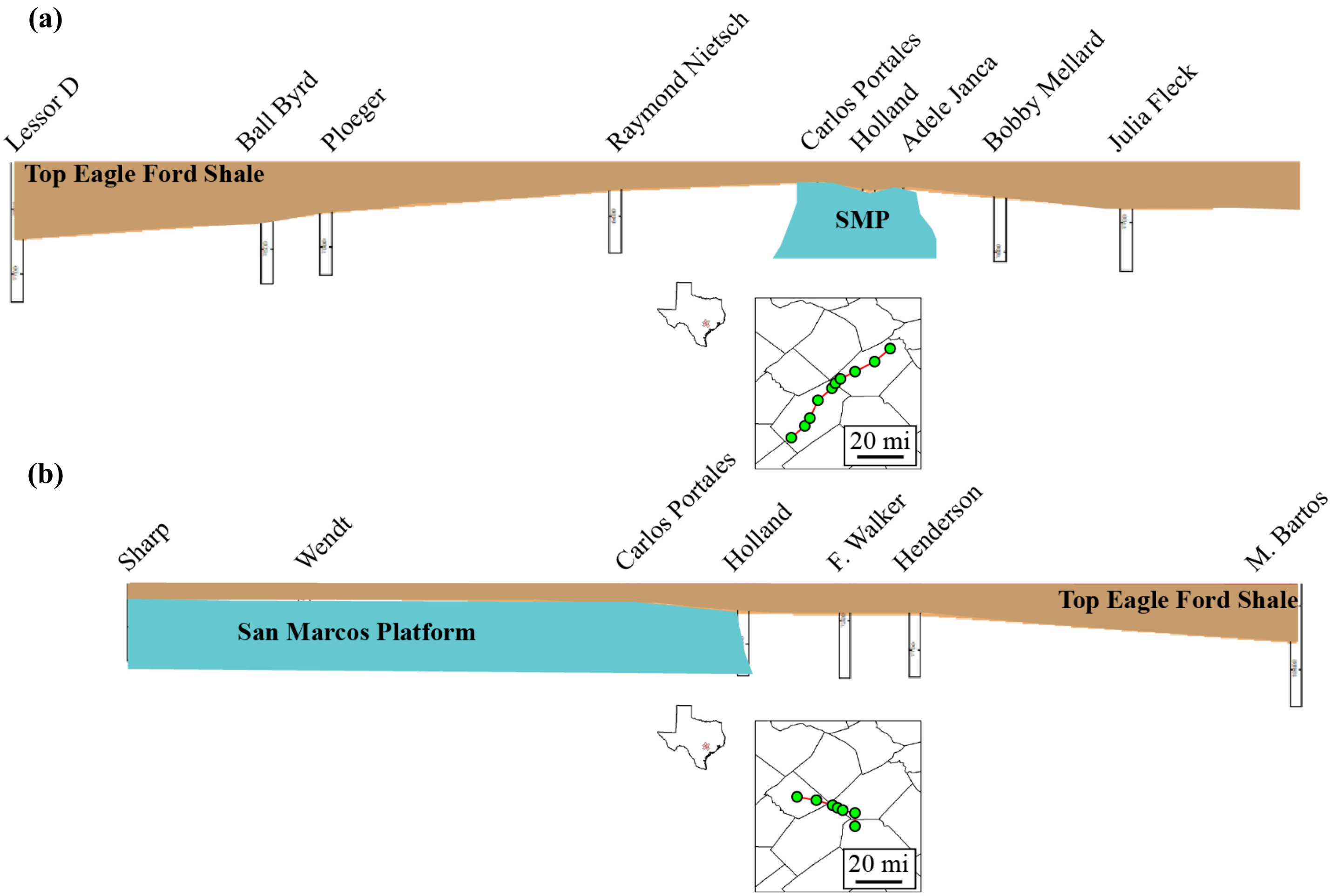

Figure 11. Cross-section datumed on Eagle Ford formation top. Rock unit thins from 120 feet (36.6 meters) in southwestern Gonzales County to 30 feet (9.1 meters) over the San Marcos Platform. Depositional trends of the Eagle Ford (mainly thinning) over the San Marcos Platform differ from those of the Del Rio. **(a)** is along regional strike, **(b)** is along regional dip.

Discussion

The depositional trends of the Del Rio Shale were examined to provide evidence for a positive structure active during deposition of the Del Rio. Thickening of the Del Rio Shale are hypothesized to represent structural lows at the time of deposition. The isopach map of the Del Rio (Fig. 10) shows that the thickest sections (where we would expect structural lows if the feature was an arch) are roughly where the San Marcos structure is thought to be located in the subsurface by numerous previous authors. Tucker's (1962) isopach map of the Del Rio showed very similar trends to the map produced for this project (Fig. 4). This also supports Laubach (1990) in that the San Marcos structure was not an overall positive structural feature during the Lower Cretaceous. In fact, the exact opposite is observed; during Del Rio time (Lower Cenomanian), a structural low could have been present where we see the San Marcos structural high in later Cretaceous strata. Another possible explanation is that the thick Del Rio section observed was the focus of a higher sediment supply, though the origin of this potential source is unknown.

As discussed earlier, Winter (1961) believed that the high-energy depositional environment of the Edwards Formation and the lower-energy environment of the Georgetown Formation represented uplift of the San Marcos structure. This would mean that the San Marcos structure was a positive structural feature during the time of Del Rio deposition. However, this is unlikely due to depositional trends of the Del Rio Shale as well as Tucker's (1962) isopach map of the Georgetown Limestone showing no thinning towards a structure of any kind.

From the cross-section in figure 9 we see that the Buda Limestone shows little if any thinning over the San Marcos structure. Rose (2016) claims the Buda mutes depositional topography, making it hard to tell if the San Marcos structure was active during Buda time. In the cross-section in figure 11, however, the San Marcos structure clearly affects Eagle Ford deposition. Little variation in thickness (calculated as 0.85 ft/mile or 0.16 m/km between the Wendt and Carlos Portales well in Figure 10b) supports Winter (1961) in her claim that the San Marcos structure is most accurately described as a platform.

Conclusion

In this study, thicker sections of the Del Rio are found where later strata were deposited in a structural high on the San Marcos structure. This means from the Lower Cenomanian of the Cretaceous to the Early Tertiary, the areas containing these thicker sections (such as in western Fayette County) possibly went from structural lows to structural highs. This change in structure could have implications about the San Marcos structure's origin and development through geologic time.

The Buda Limestone maintains a fairly constant thickness over the San Marcos structure in the study area of approximately 90 ft or 27.4 m (Figs. 5 and 9). This makes it difficult to determine if the San Marcos structure was active during Buda time. However, the Buda could have been deposited in such a way as to mute depositional topography (Rose, 2016); more evidence is required to see if the structure was active during Buda time.

Examining depositional trends of the Eagle Ford across Caldwell, Bastrop, Gonzales, and Fayette Counties showed the structure typically referred to as the San Marcos Arch to be more of a platform rather than a true arch. The Eagle Ford thins from 109 feet (33.2 meters) in western Gonzales County to 20 feet (6.1 meters) on the San Marcos structure (Fig. 11). Across this platform, the Eagle Ford thickens at a very small rate and no axis is observed. As such, "San Marcos Platform" is likely a more accurate title for the central Texas structure.

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