Place: Gulf of Mexico:

Fault Trends and the Sabine Block say the Southern Grenville Orogeny never happened

Abstract

The “hinge-line” for the rifting of North and South America in the southern Grenville Orogeny within the plate tectonics model is reviewed. The recognized “hinge-line” stretches from Chihuahua, Mexico, through uplifts to the Ouachita Mountains. In recent years it is recognized to have become detached from the location of growth for the Gulf of Mexico’s because of the volume and placement of the Sabine Block and Wiggin’s terrane. This area is examined for faults and linears reflecting the direction of stress trends. Trends do not support growth at the “hinge-line” and more recent stories have been invented to support convergence and rifting associated with the delivery of the Yucatan Peninsula to its present location. Wrongly identifying the “hinge-line” as the origin of the primary stress for the southern part of the Grenville Orogeny brings into question any geologic model that uses it. The size, circularity and concentric repetition of existing trends suggest other explanations like astral-impacts need to be considered.

Key Words: Gulf of Mexico, Grenville Orogeny, Sabine Block, Ouachita Mountains, Llano Uplift, Devil’s River Uplift, Plate Tectonics, Trends.

Introduction

Since NASA’s release of the first satellite images to research institutions in 1972, lineaments have become a significant presence in geologic studies. Gay (2012) stated, “To not attempt to understand lineaments is to ignore one of the most common and basic features in geology”. A lineament is a mappable “simple or composite feature of a surface, the parts of which are aligned in a rectilinear or slightly curvilinear relationship, and which differs distinctly from the pattern of adjacent features and presumably reflects a subsurface phenomenon” (O’Leary and Friedman 1978). I am going to extend this definition to include circular lineaments. “Linear” refers to a short segment of a lineament and “trend” identifies multiple linears that share a common stress origin and are associated by direction.

Geologist want to know what is going on in the nonvisible rocks under them. Hobbs (1911) determined that lineaments connected the visible terrane to the hidden architecture of the basement. If a single line, fracture connects the surface to basement, then multiple lines in a trend reinforces a genetic relationship. But, what made this trend?

Olgen (2004) recognized lineaments are the surface expression of fractures, joints, faults, folds, rivers, lithologic changes, vegetative cover and even cultural features which emphasize structural terrane. Lineaments are genetically related to faults, and a useful tool for locating previously unrecognized ones. Gay (2012) recognized faults as expression of shear zones. He thought thick-skinned basement faults found their expression upwards in shear trends expressed in the overlying sedimentary layers. Recognition of such linears are repeatable evidence that anyone with a little effort can verify, but the identification of the genetic source of stress is debatable.

PT is the currently reigning model for the origin of much of Earth's geomorphology, but is it trapped in the 1960’s knowledge of our planet? It assumes the Earth's crust can be divided into 8-12 major plates and many minor plates. Riding on these plates the continents have drifted over the globe, combining with each other through convergent collisions and separating by subsequent rifting numerous times over the eons of Earth's history. A creationist version is Catastrophic Plate Tectonics (Austin et al 1994), where plate movement was contained in the Flood year.

In both cases, the proponents believe multiple convergences and rifting of the plates have produced the trends of linears recognized all across the North America continent. Trends around the northern Gulf of Mexico, are thought to reflect the assembly in the Ouachita Orogeny and subsequent southern Grenville Orogeny’s rifting event, which together are modeled in PT to accounts for the origin and movement of the Yucatan Peninsula into its present position. Trend involving both thick and thin-skinned faulting are shown to conflict with this model. If these were the last PT movements in this location, their trends should be still visible like the other trends in the plate assembly of North America. But, they are not. Identifying these trends should help understand alternative explanation of their origin, and provide justification or denial for speculated plate movements. As the discovery of new trends and terranes require multiple reinterpretation, such flexibility points out the PT model is equivocal and speculative (Stanton 2002).

Plate Tectonics use of trends

PT was first proposed by Antonio Snider in 1859 connecting it to crustal plates moving during the Flood (Austin et al 2010). Frank Taylor renewed the idea in 1910 (Hoffman 2014) when he identified stress trends in the Alps and Himalayas. Based on those trends he proposed that Europe and Asia were dragged towards the equator during the Cenozoic by increased lunar gravity. In 1912 Alfred Wegener spoke of “Carboniferous Pangea and its subsequent fragmentation and dispersal” (Hoffman 2014, page 197). From these papers was proposed the concept of “continental drift.”

Tuzo Wilson is credited for the current model of Plate Tectonics. He was hostile to Taylor and Wegener’s ideas, not because he questioned the ability of continents to move, but because he deeply believed in uniformitarian ideals and felt limiting motion to only the Carboniferous through Cenozoic violated those principles.

Paul Hoffman (1988). Wilson's student and biographer, believed shear trends and linears left in the crystalline basement identify a network of smaller plates and plate fragments that converged, forming the North American Craton, Laurentia. Reading the trends in the rock's formation is the only way we can discern its history. Plate collisions are believed to produce trends of mountain ridges and concentric faults, which erode away providing the sediments needed to fill sedimentary basins. He differentiated between thick-skinned faults, through basement faults, that formed the plate boundaries, and thin-skinned faults that formed within plates.

Starting with the Superior Provence in eastern Canada (Figure 1), with its paucity of eroded mountains, he assembled North America using the assumed radiometric dating and shear trends. He joined the Trans-Hudson, Wyoming, and Hearne Provinces from the west Concurrently, from the northwest, the Rae Province acquired the Slave Province and other smaller attached island *arcs*, before attaching to the Hearne *arc*, which carried them to the Superior Shield. Later, Greenland and Iceland were added to the north, and the group of Basin and Range, and Central Plains micro blocks attached to the south (Austin et al 2010).

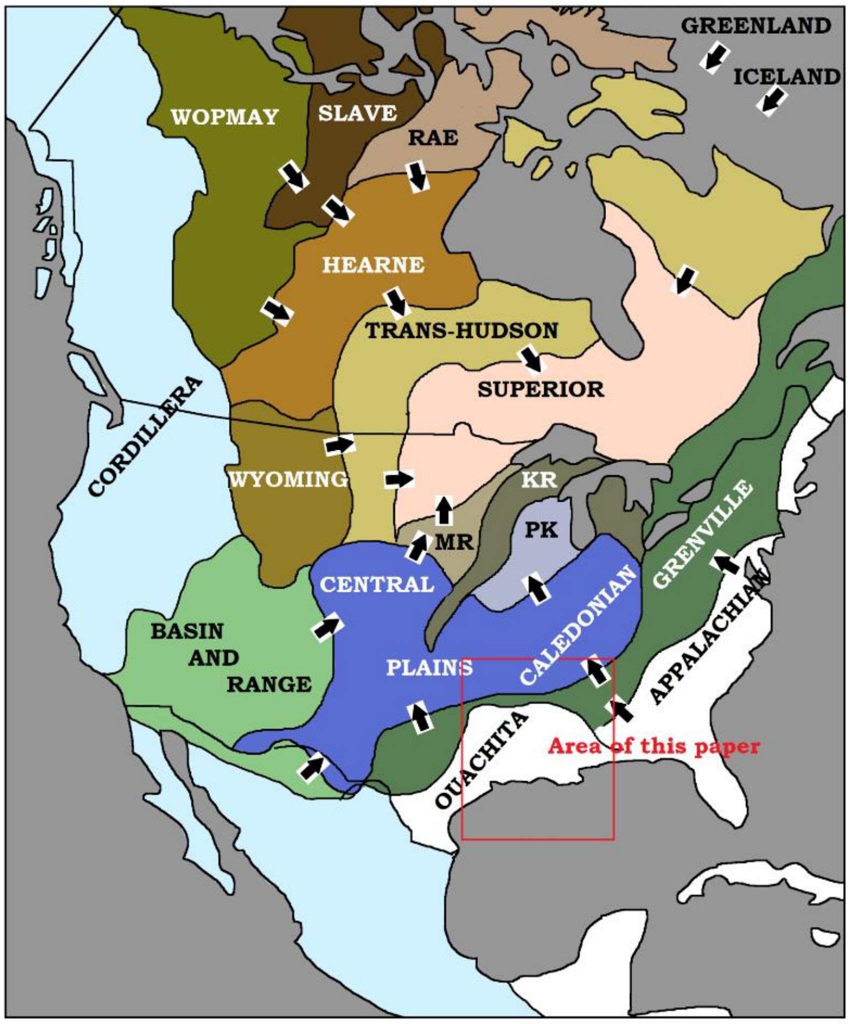

Figure 1: The North American Craton as Plate Tectonics model assembles it: KR= Keweenawan Rift, MR= Minnesota River Valley, and PK= Penokean Shield. Arrows represent proposed direction of stress and shear for verging micro plates and producing trends. Proposed pressure for Grenville Orogeny is consistently out of the southeast. Modified from Hoffman 2014.

Hoffman's scenario (Figure 2) also has the Iapetus Ocean (North Atlantic Ocean) closing at that time with other plates arriving from the northeast and Gondwana plate (Africa and South America) converging pushing up extensive Caledonian Mountains. This reconstruction is based on fit and what is identified as shared terrane (Karlstrom et al 1999). Later, Gondwana reversed its course and pulled away from Laurentia leaving only mountain remnants in the Ouachitas and Appalachians, and the few uplifts.

In these 11–12 mini-plates and collisions, Hoffman accounted for the trends he had recognized. This study (Figure 1) looks at South Central U.S.A., mapping arced trends and attempts to locate their point of applied shear.

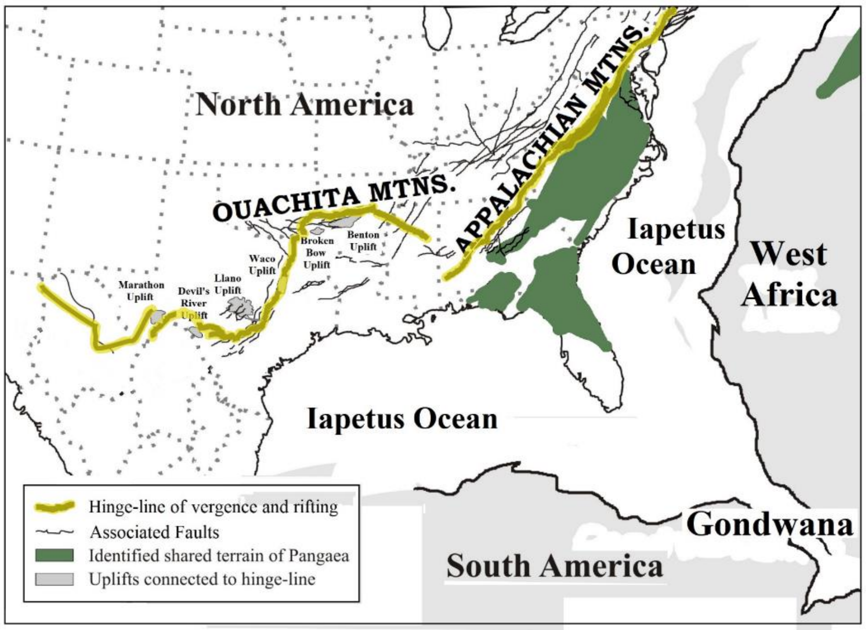

Figure 2: Proposed map of Gondwana's collision with Laurentia to form Pangaea, before rifting reopened the Gulf of Mexico. Shared terrane shown in green. Remnants of the hinge-line include the six uplifts and the Ouachita Mountains. Modified from Dennis and Wright 1997, Haenggi 2001, and Thomas 1993.

Faulting

The term “shear” trends suggest that the linears of the trend are produced by an event of large energy. Hoffman’s source of this great energy was plate pushing (convergence), producing mountains, and pulling (rifting), producing sedimentary basins. The forming of mountains and basins in brittle rock should produce faults when that rock is moved. Thus, “shear” trends implies “shear” faults.

Is Hoffman’s source of faults supported with hard evidence? Griffith, in the 1920s, thought that faults all start in brittle rock as fractures. He theorized that the pattern of fracture propagation was a random process depending on grain boundaries (location and strength of edge grain adhesion) between the minerals in the rock and the existence of micro-cracks generated by stress and strain interactions at these boundaries (Hoek 1964, Hoek and Bieniawski 1965). Inglis, in 1913, had reasoned that fractures would grow in an elliptical form as they grew larger. So combining these ideas, random fractures would start with micro-cracks at grain boundaries and propagate into ellipsoidal arcs. In 2014 Hoek and Martin suggested stress and strain were always applied perpendicular to the present fracture. Researchers (Lee and Jeon 2011, Li and Wong 2012, Hoek and Martin 2014) trying to understand faults and their growth from fractures are still trying to reason through the linear shape of some faults and the arced shape of others and the innumerable sources of stress and strain they represent.

Adding to this study, Gay (2012) recognized that faults are not often single fractures, but larger faults are composed of multiple fractures which meet at right angles. This recognizes that in larger faults, multiple sources of stress from different centers have combined. But, if Inglis was correct about elliptical shapes, why are there so many straight linears? Fractures are repeated concentrically (Barnhart 2017) and their shape, circular or straight, depends on their distance from the stress center. Mapping concentric linears and trends will locate the source of shear, perpendicular to fault. If continental drift is involved in formation of the faults we must assume faults resulting from movement must extend through the crust or continental blocks could not move. This reasoning is reflected when authors speak "of faulting and/or folding that generally overlie larger scale late Paleozoic structural features” (Webster 1980). They are trying to reason that the faults extend through the Paleozoic basement (the crust).

Trends from the Yucatan Peninsula’s movement

Many of the faults in South Central U.S.A. are believed to be remnants of Gondwana’s convergence or rifting (Figure 3). The area between the hinge-line and present location of the Yucatan Peninsula should be full of through-basement faults perpendicular to its path, or at least trends showing the one time existence of such faults, similar to the parallel linears around the Mid Atlantic Ridge. What is found instead is the Sabine Block, surrounded by through-basement faults, showing it, not the Yucatan Peninsula, was split from the craton, and it is still there. A larger picture of the stresses and trends in the South Central U.S A. needs to be viewed. If only a small fraction of the faults work with this large of a movement, the movement may not have taken place, and the Grenville Orogeny may not have happened.

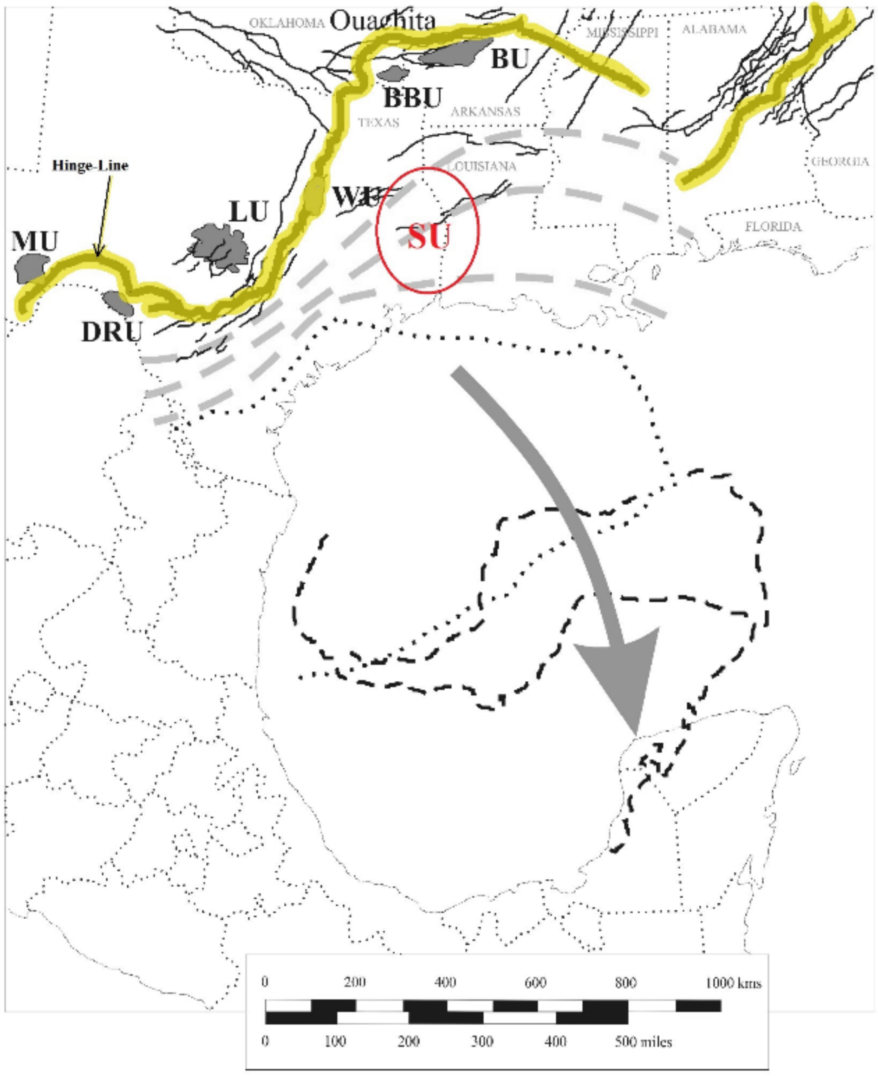

Figure 3. Location of the hinge-line and its remnants, showing the approximate path the Yucatan region is believed to have followed, and the location of the Sabine Uplift (SU) in the center of it. Abbreviations for other uplifts: BBU= Broken Bow Uplift, BU= Benton Uplift, DRU= Devil’s River, LU= Llano Uplift, MU= Marathon Uplift, and WU= Waco Uplift.

Concentric Faulting of the Ouachita Orogeny

What is the prominent expression of faults around the southern Grenville Orogeny's convergence and rifting? Figure 4 traces the faults shown on a standard USGS geological map (Ewing 1991) of the area. The fault mass at A is the most visible trend. These are relatively shallow normal faults and are generally identified as extension faults (Arbenz 2008, Mordelli 2010). But, they cross the block below the Sabine Uplift. Therefore, they are not extension faults reaching through the basement.

Faults piercing deep into the basement, as Hoffman (1988) had suggested, was needed for plate movement do exist in addition to the shallower faults of Figure 4. However, they do not follow the path of the Yucatan movement. Rather, they follow the circular arc to the Gulf of Mexico from the Mexican coast to Florida. This trend led Stanton (2002) to suggest an astral-impactor origin for the gulf basin.

Most of the faults pictured are listric faults (Peacock et al 2000) whose fault angle flattens with depth. Had these listric faults penetrate the crust and produced plate growth, they should show volcanic evidence of that penetration, such as the Ring of Fire around the Pacific Ocean or the Mid Atlantic Ridge. In Figure 4, trend A of faults are in the most productive petroleum producing area of the Gulf of Mexico where well cores show only minor amounts of volcanics. So, while the faults at A are the right direction to contribute to the Yucatan region's move by extending the crust, they give no evidence of having done so as they are too shallow. Listric faults are commonly seen in slumping situations, as in the slumping of unconsolidated sediments. These listric faults form Trend A, and using the principle that the source of shear is perpendicular to the trend of faults, the source of shear for Trend A's slumping is towards the deepest part of the Gulf of Mexico.

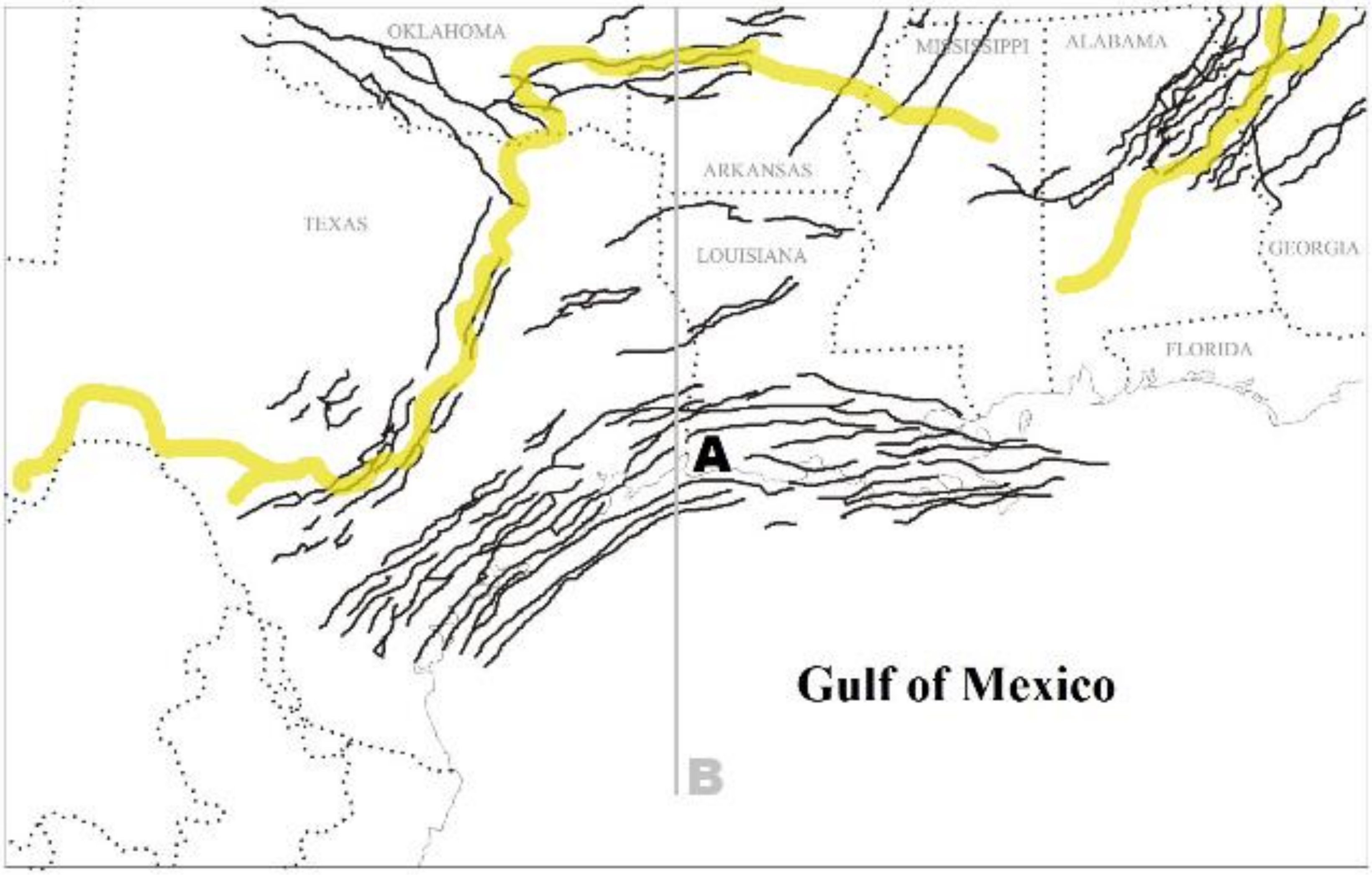

Figure 4. USGS fault map of a portion of the hinge-line, shown in yellow. (A) Location of trend A. Other surrounding fault believed to contribute to the Grenville hinge-line. This portrayal of these faults is largely simplified from Figure 5. (B) Location of cross section for Figure 12 and 13. (Source of faults, Ewing 1991.)

While the faults for the Grenville Orogeny are generally presented as in Figure 4, these are selected from a much larger array (Figure 5). Their selection seems to be governed by how well they fit into the generally accepted consensus view. Caran et al. (1981) maps a much broader orientation of fractures expressed in surface linears graphed from Landsat photos (his Figure 3) and subsurface isotherms from well readings in aquifers across this area (his Figure 4). They found the subsurface trends to be consistent with the Landsat trends, and hence, while faulting was not always apparent, their conclusion was linears were fault-controlled, but they could not determine to what depth they penetrated. Although some trends and faults in Figure 5 do correlate with the direction of the hinge-line, many individual linears follow Trend A.

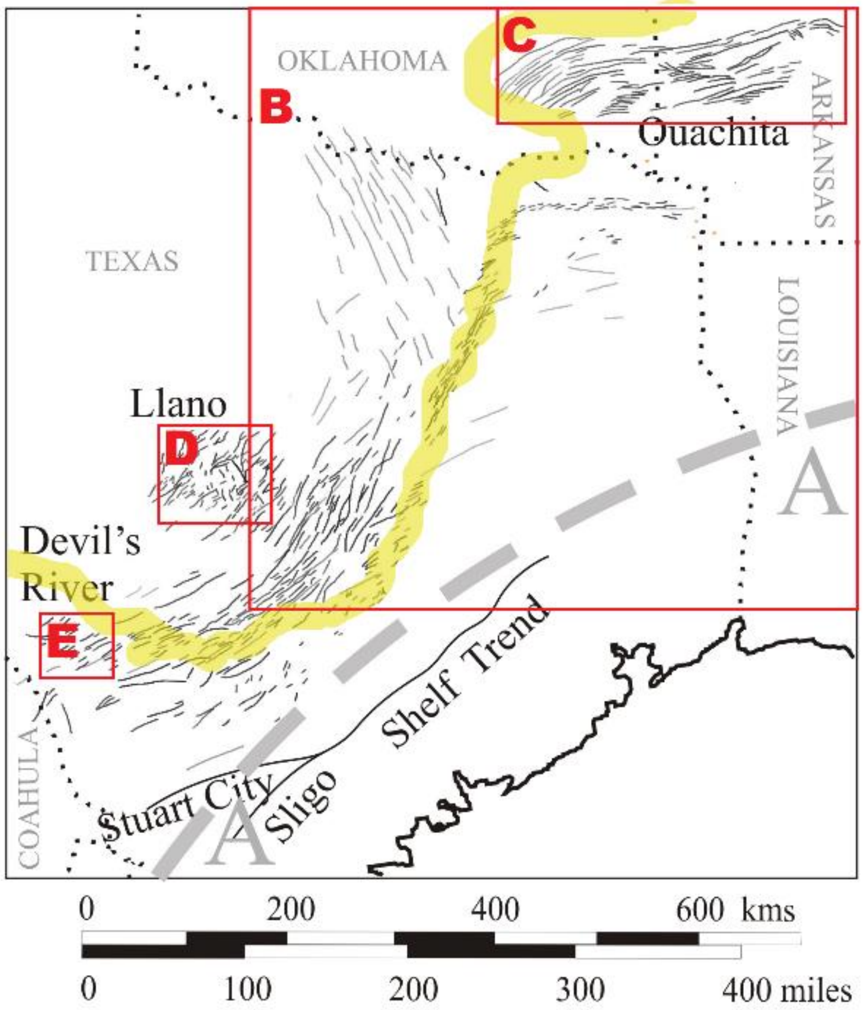

Figure 5. Linears associated with the hinge-line, shown in yellow, compared with Trend A. Devil's River, Llano, and Ouachita faults added for comparison. Location for each of the details, (B) Complete Bouguer Anomaly map (Figure 7), (C) Ouachita Mountains (Figures 8 and 9), (D) Llano Uplift (Figure 10), and (E) Devil's River Uplift, (Figure 10). Modified from Caran et al 1981.

Seni and Jackson (1984) map part of the same area in greater detail (Figure 6). They mapped preferentially the faults associated with the direction of the hinge line, and these linears correspond to the dark trend across Figure 5. The Balcones, Luling, Mexia, and Talco Fault Zones show faults that correspond to the hinge-line, but they also show individual faults consistent with Trend A.

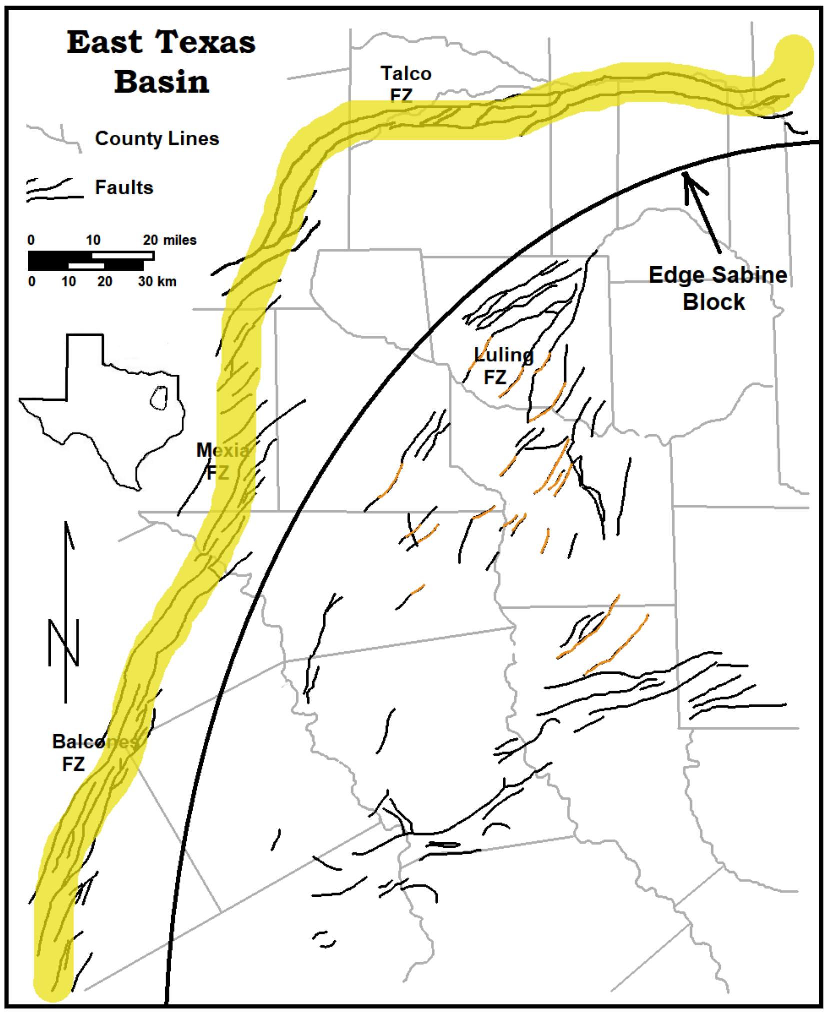

Figure 6. Charting of faults in the East Texas Basin, showing the fault zones (FZ) associated with the hinge-line, shown in yellow, and the approximate edge of the present Sabine Block (Modified from Seni and Jackson 1984.)

The Sabine Block is about 820 km (510 mi) long, the same length, and occupies the same space ascribed to the Yucatan peninsula's origin. Since rifting is thought to produce thinning extensional crust with normal faults, the crust would not thicken under the normal/ extensional faults, replacing the "Yucatan" block with another block just as thick.

Other Trends

Figure 7 shows trends across northeastern Texas from the Complete Bouguer Anomaly contour map (Dutch 2013, Kruger and Keller 1986). Bouguer maps graph gravity, the density readings, that are thought to be most divorced from topography and the thickness of the crust (Dutch 2013). Trends are seen in small disruptions to the smooth expression of contours (Chapter 1). The Ouachita Mountains form an abrupt gravity ridge in the northern half of Figure 7, Trend A. Other trends in Figure 7 have been interpreted as circular or arcs as portions of circles. Many form concentric circles lineaments which Chapter 2 determined raised the confidence in their identification since concentric circles do not occur randomly. This would support the possibility that each of these circles represent a point stress, which could be an impactor. Trend T is connected with the TONCK impactor structure (Chapter 1).

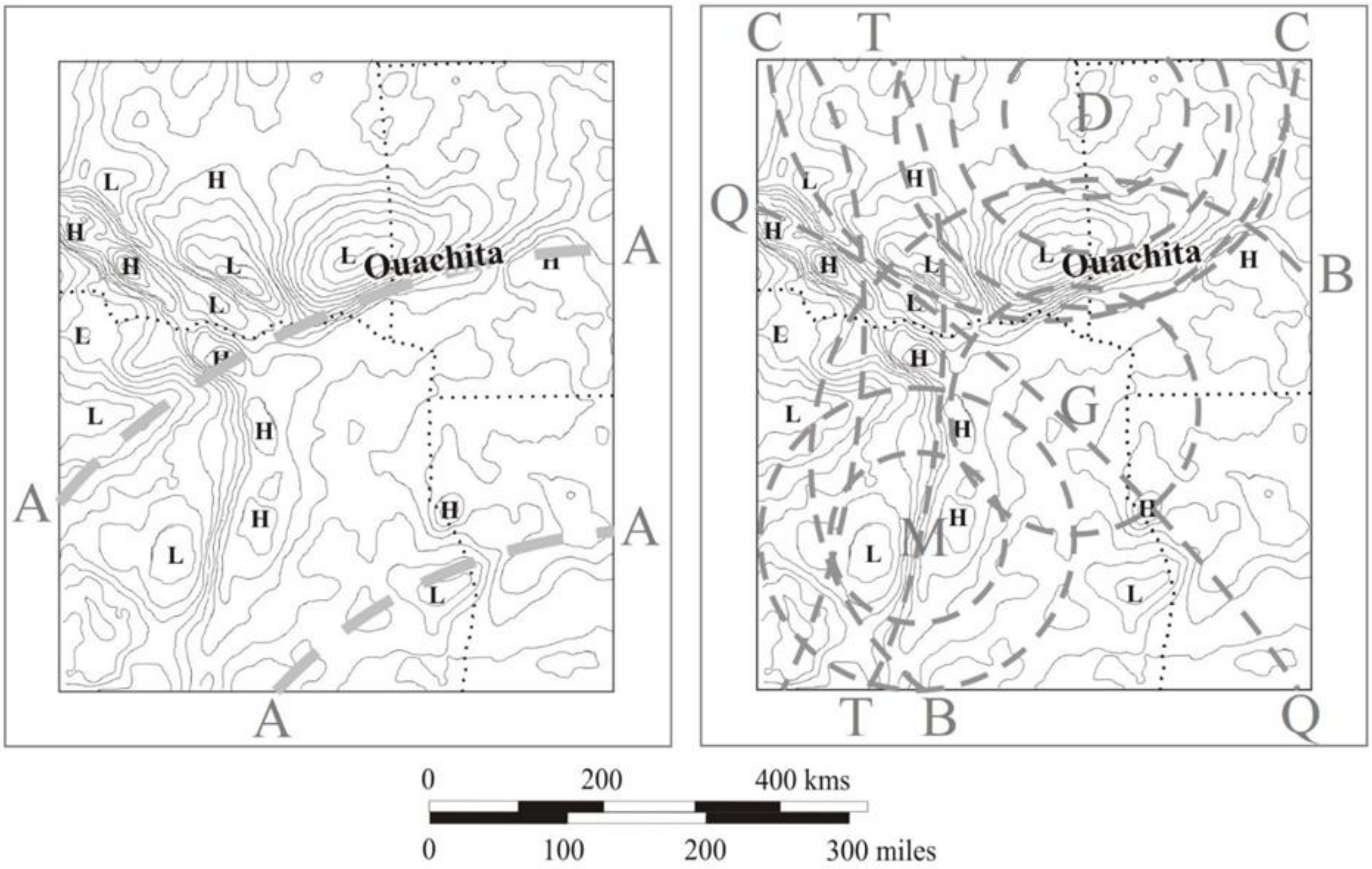

Figure 7. Northeastern Texas, Oklahoma, Arkansas and Louisiana's Complete Bouguer Gravity Map. Upper, showing most prominent Trend A. Lower, showing other trends indicated. State borders shown as gray dotted lines. (Bouguer map simplified from Dutch 2013, and Kruger and Keller 1986.)

Ouachita Mountains

The Ouachita Mountains (Figures 8) are a sandwich of stacked layers turned up on edge. Alternating layers of two different Pennsylvanian and a third Mississippian deposit are all stacked around the Broken Bow Uplift on the western end, while Ordovician and Pennsylvanian deposits alternate with Cambrian material around the Benton Uplift on the eastern end (Richard et al 2002, Shaulis et al 2012). Miser (1929) showed that these stacked layers on the western end were thrust faults stacked en echelon. But, in spite of the lithologic difference of these two areas, note that many of the faults at both ends align with the general line of Trend A (Figure 9 Upper), showing that those linears share the same source of shear as Trend A. Some of the linears of the trend are faults while others linears are gaps in fault expression. Shockwaves are expressed in both the shock wave, thrusting faults and the following rarefaction/ release wave (Barnhart 2017) producing gaps in fault expression.

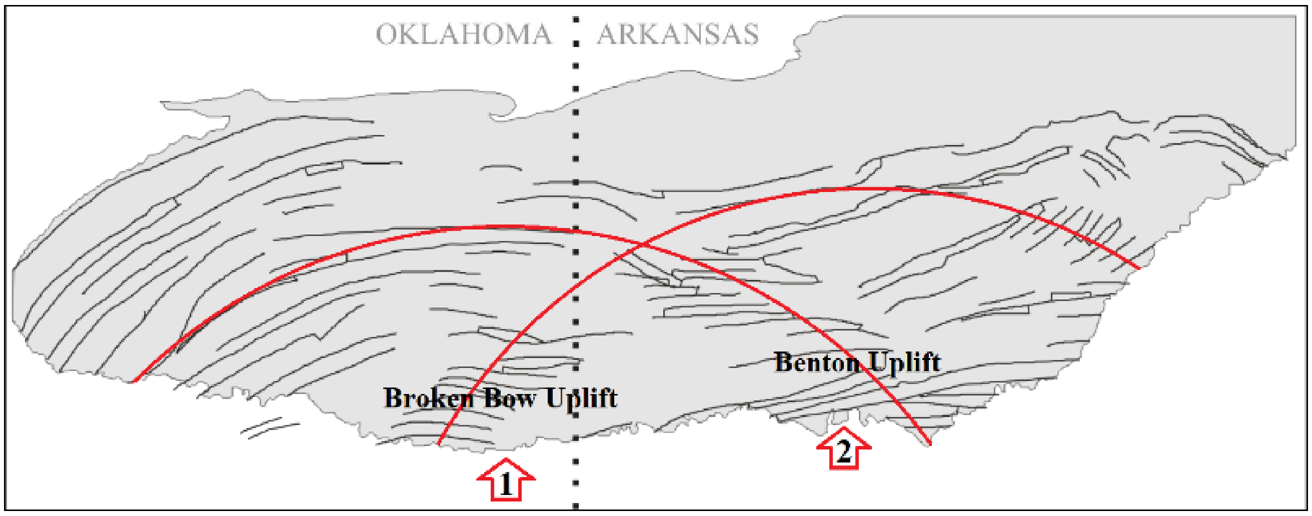

Figure 8. The fault pattern of the Ouachita Mountains north of the Gulf Coastal Plain. Arrows 1 and 2 express sources of shear.

Trend B and C (Figure 9 lower) define the north and south edges of the Ouachita Mountains without faults, but expressing the limit of other faults. Trends E and F have different sources of shear but cross in the center as the division between faults of the western and eastern halves.

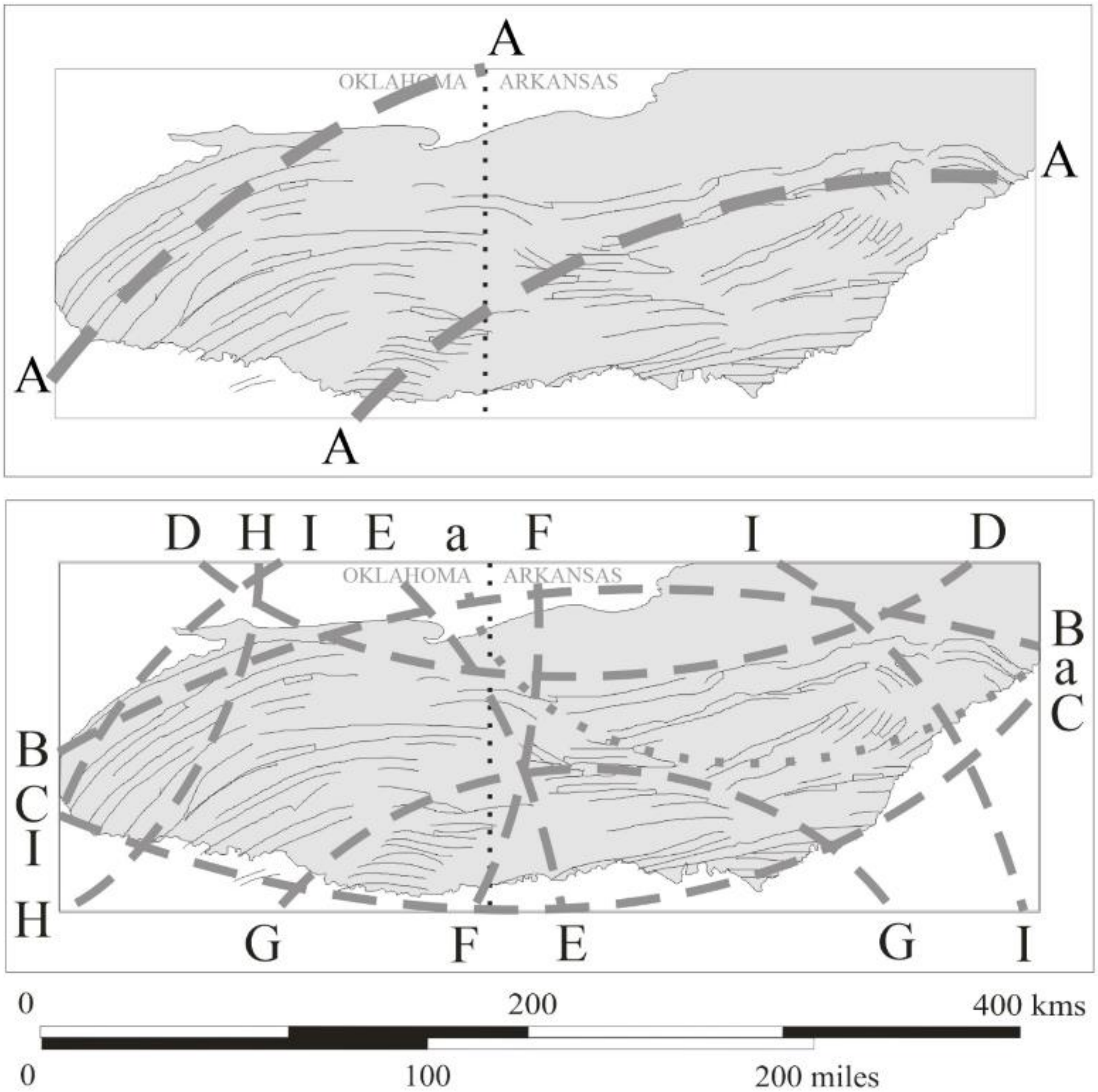

Figure 9. Trends of the Ouachita Mountains. Upper shows Trend A is not lost. Lower, many other trends are also prominent. (Lower case letters designate trends that are not mapped beyond this image.)

From Llano Uplift of Texas through the Devil's River and Marathon Uplifts into Mexico (Figure 3) less faults are mapped and the hinge-line is believed to take an abrupt turn from Devil's River to the west (Figures 2). The lineations and faults do continue south, Figures 5 and 11, in association with Trend A, but they are normally ignored as not conforming to the model, so thus not important. In Figure 10 both uplifts center on a circular pattern, Trend O for Llano Uplift, and Trends R and S in Devil's River Uplift.

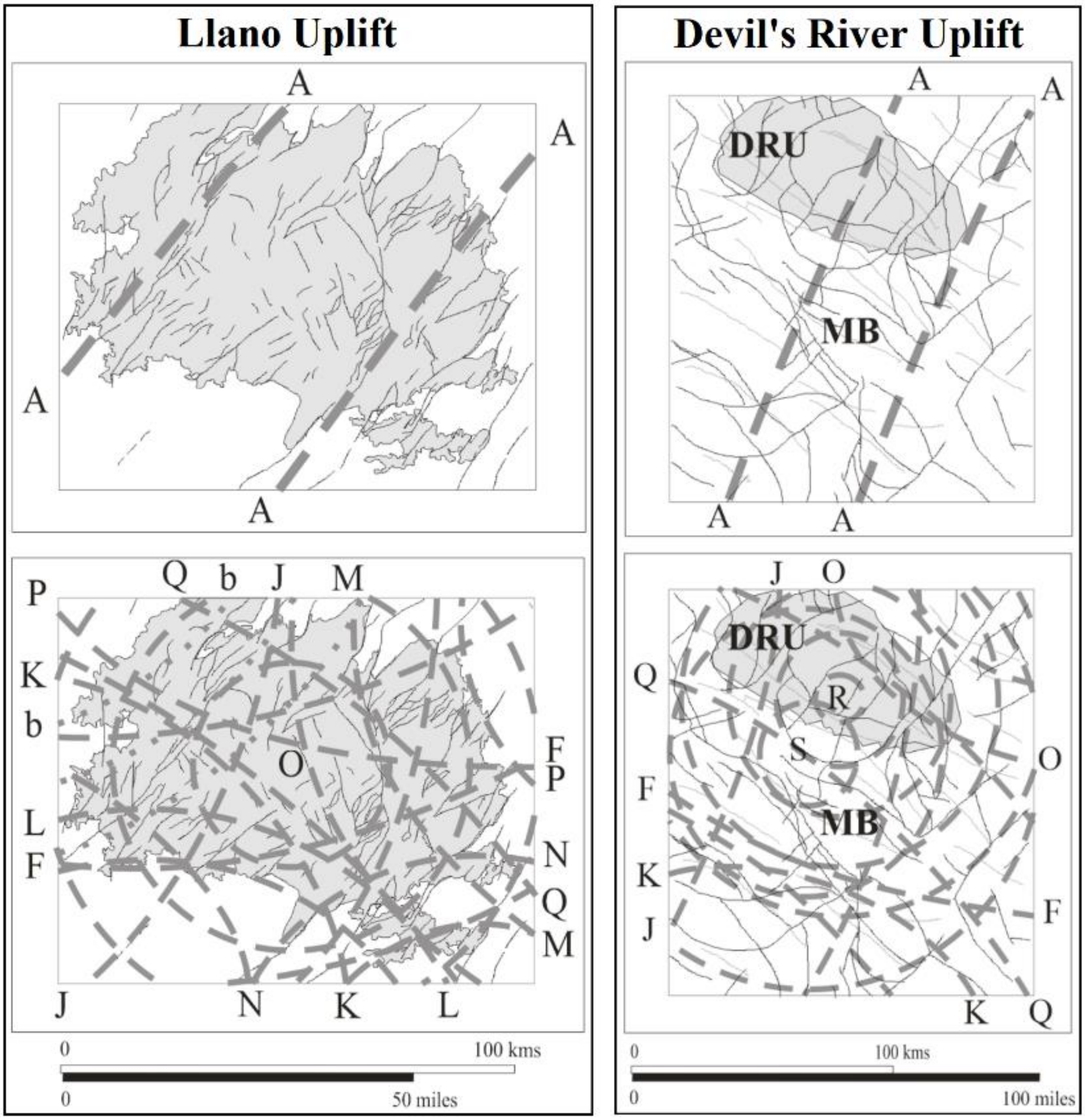

Figure 10. Map of the faults of the Llano and Devil's River Uplift showing trends. Upper shows the prominence of Trend A. Lower shows other prominent trends. (Lower case letters designate trends that are not mapped beyond this image.) (Llano after Caran et al 1981, Ewing 1991, Mosher et al 2008, and Reed et al 1998, Devil's River Modified from a seismic/magnetic interpretation by Alexander 2011.

Sabine Uplift

Because of its location, the Sabine Uplift creates problems for the Grenville Orogeny and the Plate Tectonics Model (Figure 3). Very few faults define its edge (Figure 6), showing the sedimentary strata was not involved in any movement.

Mickus and Keller (1992) provided a cross section of the block from the surface to the Moho, so the general structure is known. Arbenz (2008) and Mondelli (2010) reconstructed the rifting stage of the Grenville Orogeny, Figure 11. They imagine the block was split by Gondwana's rifting, with a sizable section of extended crust developing to the north, and an ultimately more successful rift to the south. The ultimate success of this more southerly rift allowed the incipient rift in the center of the block to close. They take for evidence fine volcanic breccia found in the Eagle Mills (Wade 1993, Mancini et al 2008).The Eagle Mills is a layer of lithic breccia cemented with red clay that is the first layer above the crystalline basement of the Sabine Block, and extend east to Florida and south to Veracruz, Mexico. But in spite of the presence of volcanics, Mickus and Keller (1992) found no evidence of through-basement faults within the block, so no incipient rifting took place from Florida through Mexico, and the Grenville Orogeny did not take place here.

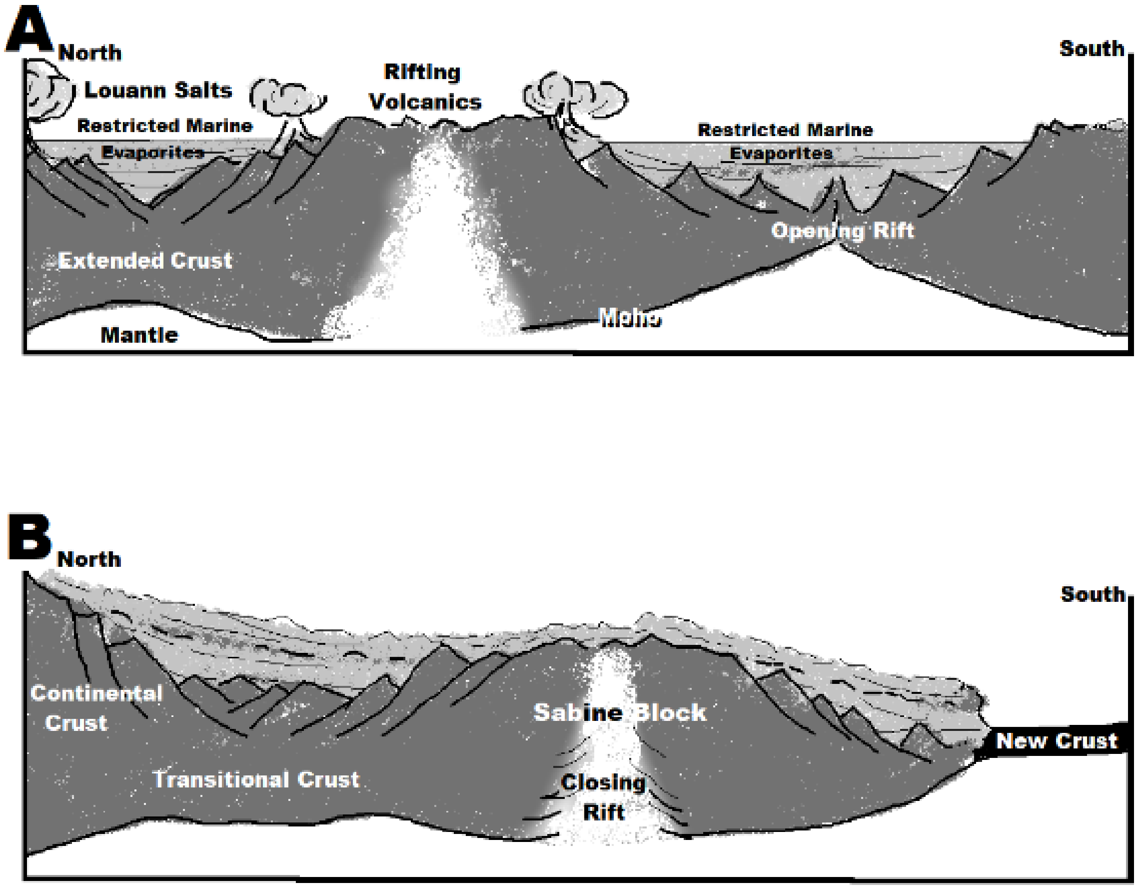

Figure 11. (A) The rifting of Gondwana away from the continent, and subsequent rifting through the Sabine Block. (B) The extension of transitional crust to the north, allowing the rift to close. New oceanic crust to the south filling in as the new rift succeeds. After Arbenz (2008) and redrawn from Mondelli 2010.)

Looking at the details of Mickus and Keller's reconstruction (Figure 12), the Sabine Block shows an upper and lower half like the crust. While the top half of each is the same density, the lower half in the block is denser, like it was compressed. At (1) and (2) in Figure 13 the block meets the new ocean crust at each end. I interpret that the block was blasted out of the crust and settled back to float on the mantle. The slightly higher density of the lower block was produced by the shearing force's compression. The thinner new crust at (1) (Figure 13) would interpret as the isostatic adjustment occurred after the new crust had started to form, reflecting how fast the process proceeded. The captured metasediment (3) (Figure 13), include the Morehouse Formation (with Pennsylvanian pollen, gastropods and pelecypods (Mancini et al 2008) was probably part of Ouachita sediments), were buried deeply, with breccia of the blast (4) and metamorphosed by its heat and pressure. An adiabatic pillow of lower density (3.15) produced by the release wave's (Barnhart 2017) movement under the block remains.

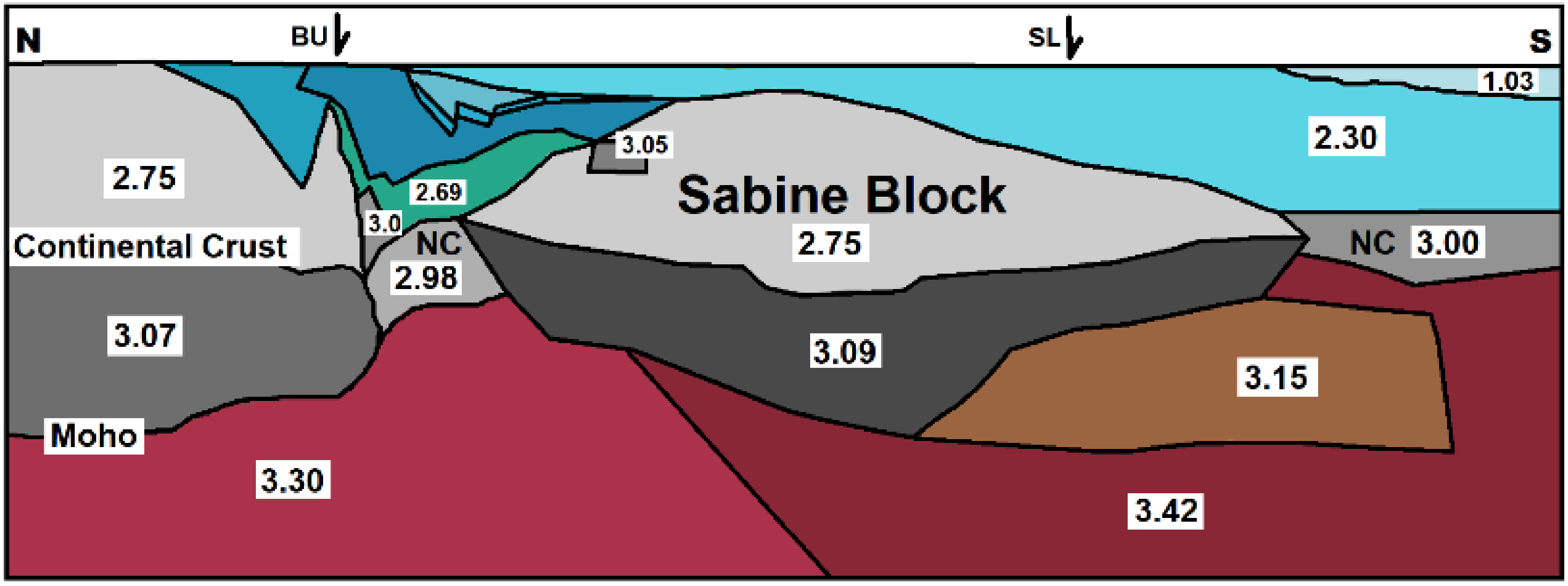

Figure 12: Sabine Block and associated continental crust showing densities determined by Mickus and Keller showing the pillow of adiabatic pressure under the basin-ward side of the block, NC= New Crust, SL= Shoreline, BU = Benton Uplift and the spire of granite below it. (Modified from Mickus and Keller 1992.)

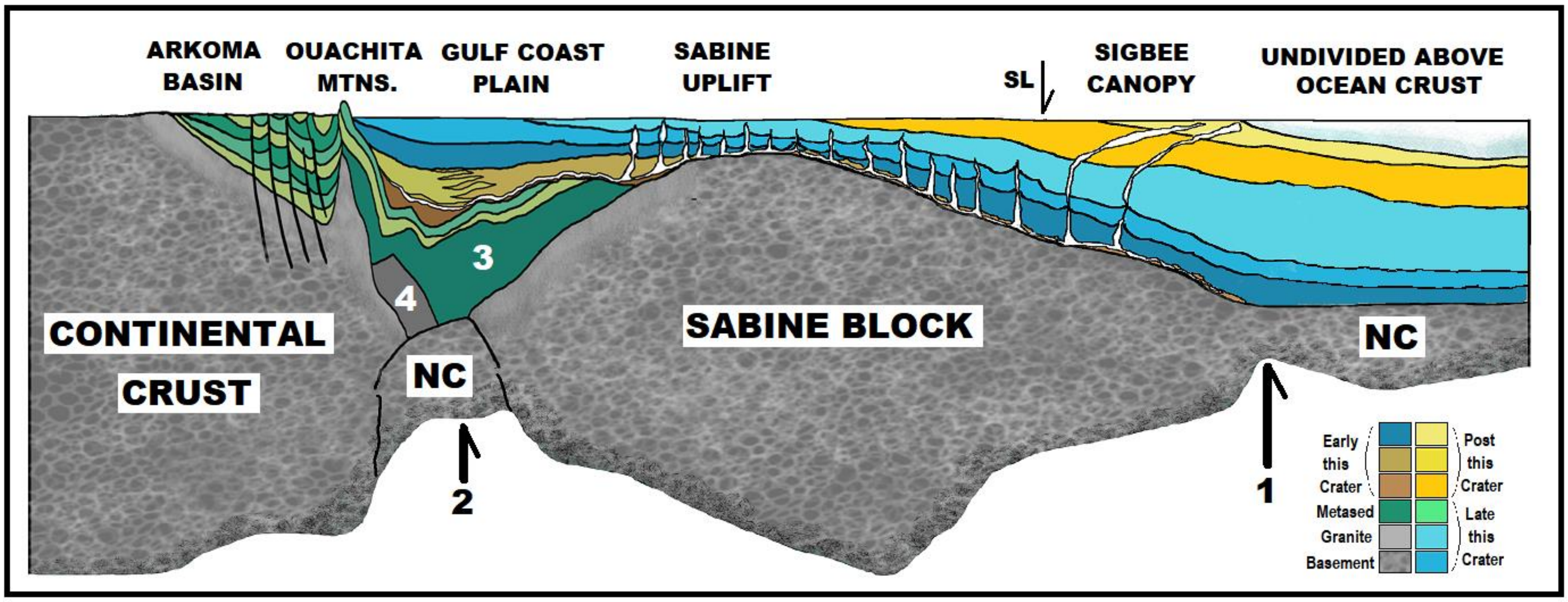

Figure 13: The Sabine Block with its sedimentary cover. (1) New crust below the original upper point of the block, which dropped as it settled into isostatic balance on the mantle. (2) Connection between the block and new (thin) crust. Upward flexure at 1 showing this settling occurred while it was reforming. (3) Metasediments blasted from the block's underside in the Crowning Event. See Figure 4 for location. (Modified after Mickus and Keller 1992.)

The Sabine Block: an impactor origin scenario

An alternate scenario for formation of the Sabine Block in an impactor event forming the Gulf of Mexico crater is offered. A large impactor struck the crust and burrowing rapidly to and through the Moho. The impactor generates a shock wave (Figure 14A) that excavated the crater (Barnhart 2017, Osinski and Pierazzo 2013) in a crowning event of ejected breccia moving rapidly outwards. The impactor's energy carried the shockwave expression below the Moho (Figure 14B) where part of the energy is trapped below the crust, breaking off a section of crust too large for ejection. As the energy from the shockwave was expended, the block reached isostatic balance, floating on the viscous mantle, trapping the lower density pillow underneath. These actions produced significant amounts of vaporized substrate joined by vaporized magma from the mantle. As the mantle 'skins-over' the clouds of vapor start to cool and crystallize, dropping authigenic sediments and pieces of hot rubble (volcanics) in the fall back of the Eagle Mills formation.

Miall (2008) proposed three northward thrust points for the Ouachitas. I propose only two (Figure 8). One centering around the Broken Bow uplift on the west and the other centered on the Benton Uplift on the east (his third point is between those). The pressure of lifting the Sabine Block in the crowning event was deflected to the sides of the block's keel, shown as arrows 1 and 2 in Figure 8. The pressure's energy signature is recorded in the separate occurrence of the Broken Bow and Benton Uplifts, where there are continuous sediments from the Ouachitas on both sides of these uplifts (Figure 13) between lithic fragments and metasediment and below the Gulf of Mexico's sediments.

A map of the Great Unconformity (Marshak et al 2017), Figure 15, for the craton portion of the continent (north of the wide gray line in Figure 15) includes the Arkoma Basin, Oklahoma to Arkansas. When the Sabine Block is put into place and the direction of its thrust in a crowning event is modeled, it shows the Arkoma Basin was probably already present and the energy signature of that crater had a significant affect where the Sabine Block's northern edge broke free.

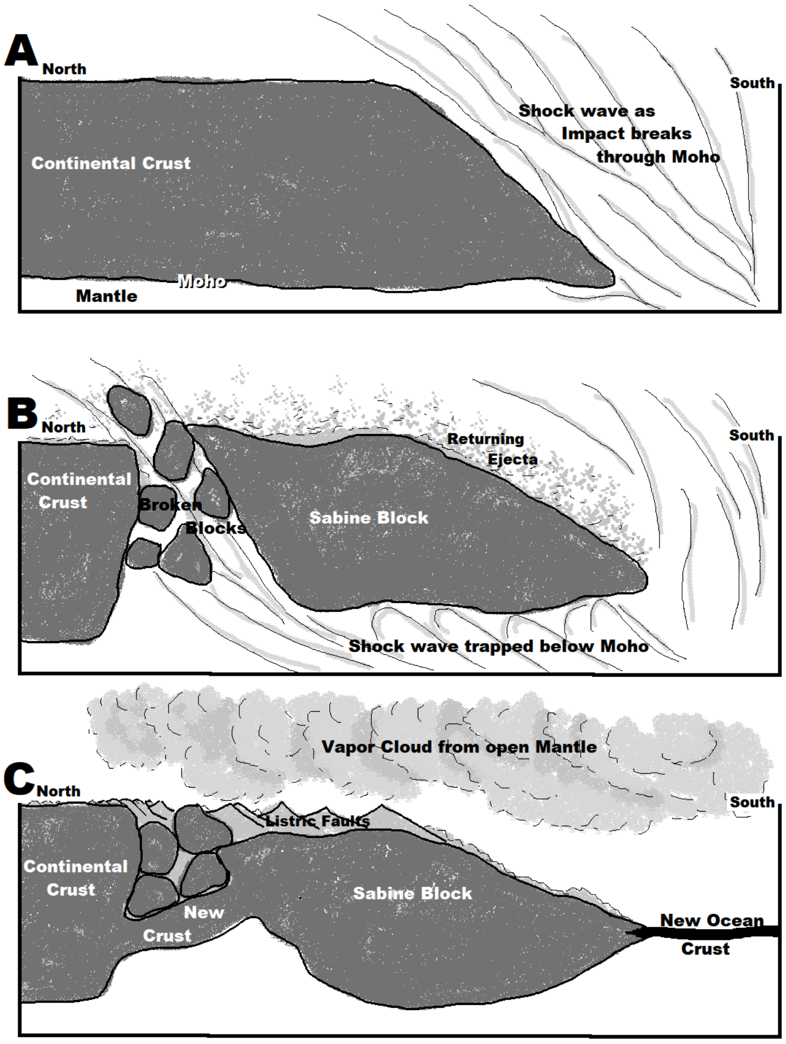

Figure 14: Possible scenario for formation of the Sabine Block from an astral-impactor cratering event. (A) Impactor strikes and shock wave blast a crater which breaks through the Moho. (B) As the shock wave continues into the mantle, a portion is captured under the crust and breaks off the Sabine Block in the Crowning Event. The first fall of returning ejecta, characterized as volcanics, starts to collect on the crater surface as outward thrust is diverted. Vaporized magma rises through the open mantle. (C) New crust forms as mantle openings “skin-over,” sealing them, leaving vapor clouds of magma to condense and supply authigenic sediments.

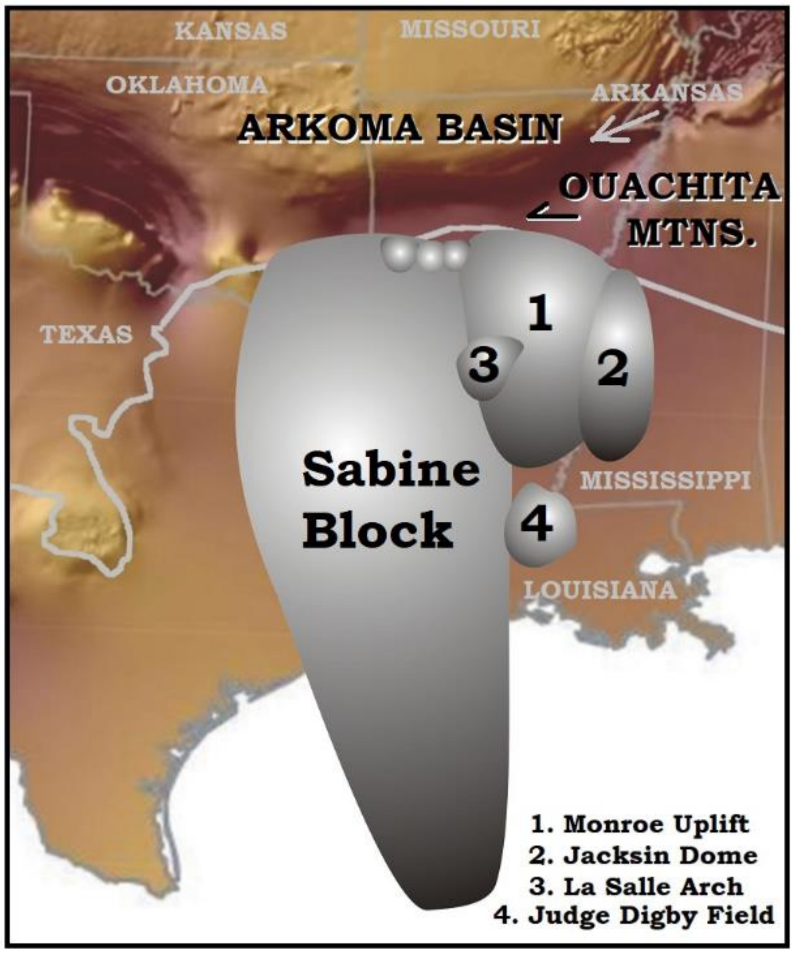

Figure 15: Sketch of possible shape of Sabine Block and associated rubble from Gulf of Mexico impactor cratering event. Shown on a Great Unconformity Map, with data plotted north and west of wide gray line and artist rendering south of that line by author. (Map data used with permission of Marshak 2017.)

Conclusion

The idea of an astral-impactor cratering event of this magnitude is new, but the moon’s South Pole-Aitkin, 2500 km (1550 mi) diameter; and Mar’s, Hellas, 2300 km (1430 mi) diameter, are the same size range on smaller astronomical bodies, demonstrating the possibility. Traditional Plate Tectonics, Grenville Orogeny, and Catastrophic Plate Tectonics are well accepted and comfortable ideas that are being called into question. Is there any reason to even contemplate a radical alternative such as impactor cratering?

If Trend A (in figure 4. 5. 7, 8, 9, and 10) is as significant in the Ouachita Mountains, Llano Uplift, and the Devil's Creek Uplift as its occurrence implies, something of exceptional power happened in the central Gulf of Mexico, greater than any other source of energy expression in that area. And, it left a record in the rocks far greater than any evidence for the Grenville Orogeny. Additionally, Trend A's occurrence around the Benton and Broken Bow uplift of the Ouachita Mountains (Figure 9) and the other uplifts, representing the remains of the Ancient Ouachita Mountains, means Trend A date back to the original thrust that put the Ouachita Mountains, not the Caledonian or Ancient Ouachita Mountains, in place around the Broken Bow and Benton Uplifts, and this information shows it dates to the thrust of the Sabine Block and not the convergence of the Grenville Orogeny.

Did the Southern Grenville Orogeny ever happen?

As impactors come in all sizes, it is reasonable that they should produce faults of varied penetration. If the Ouachita Mountains were pushed up by a collision of the Sabine Block striking the continental crust and the block still occupies that location, then the Yucatan region never occupied this place and the convergence and rifting of the southern Grenville Orogeny did not happen as Plate Tectonics models it. Then how did the Gulf of Mexico come into being? Next we will look at information concerning the formation of the gulf can be gleaned from the structure of the associated mountains.

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