Aeromagnetic Map Constrains Jurassic-Early Cretaceous Synrift, Break Up, and Rotational Seafloor Spreading History in the Gulf of Mexico

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Abstract

We present a reduced-to-pole, total magnetic intensity map derived from merged aeromagnetic surveys in and around the Gulf of Mexico. Most of the deep central Gulf crust has a magnetic pattern of orthogonally intersecting features similar to, and interpreted as, fracture zones and ridge segments of oceanic crust formed by seafloor spreading. This spreading or drift phase occurred after the primary synrift phase of continental stretching across the greater Gulf of Mexico region, and thus the ocean crust rests within a broader zone of stretched continental crust with Yucatán, western Florida, the southern USA, and eastern Mexico forming the surrounding continental margins. We identify three regional magnetic anomaly trends that can be used to constrain the Gulf of Mexico's Late Jurassic through earliest Cretaceous spreading history. A central magnetic anomaly trend is interpreted to accord with the later increments and cessation of seafloor spreading, for which a stage pole of rotation is estimated. Two flanking magnetic anomaly trends to the north and south of the central one, respectively, occur just basinward from the inferred depositional limits of autochthonous Callovian-Early Oxfordian salt. These anomalies appear to define the landward limits of oceanic crust in the northern and southern Gulf, and probably lie in crust that is medial or Late Oxfordian in

age. They have similar mapped patterns that can be reconstructed onto one another and hence are probably genetically related but separated by spreading. These landward anomalies are best fit around a different stage pole than the central anomaly; thus the rotation pole appears to have jumped during spreading in the Gulf. Seismic reflection data show that the two outer anomalies occur at the basement "step ups" to the oceanic crust or the basinward shoulders of the "outer marginal troughs." Until specific magnetic source modelling is done on the outer anomaly pair, we favor an edge-effect interpretation caused by the intrusive interface between Oxfordian oceanic crust and serpentinized and exhumed subcontinental mantle, the latter of which we infer forms the step ups to the oceanic crust. In addition, the aeromagnetic map shows a north-south trending "Campeche Magnetic Anomaly" downslope from the western shelf edge of Yucatán that we argue helps to constrain the reconstruction of Yucatán along Texas at the start of the synrift stage. Thus, the aeromagnetic map provides vital insights into the kinematics of all three stages of the basin's development, namely the synrift, the drift, and the interpreted intervening transitional phase of crustal hyperextension/mantle exhumation along the Gulf's magma-poor continent-ocean transitions.

Introduction

The Gulf of Mexico is generally thought to have originated in distinct rift and drift phases. Late Triassic-Middle Jurassic northwest-southeast synrift stretching of the continental crust occurred across the greater Gulf of Mexico region while seafloor spreading was already underway in the Central Atlantic. This was followed by anticlockwise seafloor spreading about a nearby pole in the Florida Straits that created the central Gulf's oceanic crust and separated an originally continuous end- or slightly post-rift salt basin into the two halves we know today as the Louann and Campeche salt provinces (Pindell and Dewey, 1982; Pindell and Kennan, 2009; Hudec *et al.*, 2013). The pole of rotation for Phase 2 drift was situated so nearby that continental rifting ensued without seafloor spreading in the Florida Straits of the southeastern Gulf (Martön and Buffler, 1999).

Public magnetic datasets remain unable to constrain comprehensive models of seafloor spreading in the Gulf of Mexico due to inadequate data coverage, thick sedimentary sections, and the low paleolatitude of the Gulf in the Jurassic (<15°N; González Naranjo *et al.*, 2008) resulting in shallow magnetization vectors that subdue magnetic intensity at the surface. In this paper, we present a regional aeromagnetic map that shows systematic structural patterns attributable to seafloor spreading and continental break up for the majority of the Gulf of Mexico.

Aeromagnetic Map of the Gulf of Mexico: Primary Observations

An aeromagnetic survey was conducted in 2003 over the Mexican portion of the Gulf of Mexico, and an integrated onshore-offshore reduced-to-pole (Baranov, 1957) total magnetic intensity aeromagnetic map was prepared (Fig. 1). The survey had an east-west line spacing of 3 km, a north-south spacing of 9 km, and a flight altitude of 300 m. Onshore aeromagnetic data had been collected in the 1970's and 1980's in various surveys ranging in elevation from 450-3000 m. Integration of the datasets was conducted for an altitude of 2500 m, applying "upward continuation" for surveys <2500 m, and "downward continuation" for surveys >2500 m. U.S. portions of the map were compiled in conjunction with a private source and integrated accordingly.

The aeromagnetic data and map are owned by Pemex and partly published by CNH (2015), Cerón (2007), and Rocha Esquinca *et al*. (2013). We present a version of the map that is scaled to best portray basement structure.

In the onshore and shelf areas thought to comprise variably rifted continental crust, the map reveals long-wavelength, rounded or oblate magnetic anomalies. Noteworthy is the north-south magnetic high outboard of the western Yucatán shelf margin that we term the Campeche magnetic anomaly, similar in geometry and intensity to the better known Houston and Florida magnetic anomalies of the northern continental margin. Deep seismic data show that the Florida (Imbert and Philippe, 2005; Pindell *et al*., 2011) and Campeche (Goswami *et al*., 2016) anomalies likely pertain to volcanic flows within synrift sections of rift basins; a similar origin has been suggested for the Houston anomaly (Mickus *et al*., 2009).

In contrast, the magnetic anomaly pattern over the deep Gulf comprises linear and orthogonally intersecting trends, from which we make seven primary observations of greatest interest here. Figure 2 shows our interpretation discussed below; Figure 2 may help the reader to locate the seven primary observations made here.

Observation 1

A broad central zone of high magnetic intensity occurs about midway between the northern and southern margins of the Gulf. This magnetically strong zone, which we term the Central magnetic anomaly trend (CMAT), has a clear pattern of elongate magnetic highs and lows that are interrupted by shorter wavelength, orthogonally crosscutting linear features.

Observations 2 and 3

Two additional anomaly trends occur in the northern and southern portions of the Gulf, the Northern magnetic anomaly trend (NMAT) and the Southern magnetic anomaly trend (SMAT). Both comprise several linear or elongate highs that are truncated sharply by shorter wavelength linear trends. The northern and southern anomalies are fringed to the north and south, respectively, by magnetically subdued zones that extend to the bases of the Florida and Campeche platform escarpments, and beneath the Sigsbee Escarpment.

Observation 4

The western boundary of oceanic crust in the Gulf, called the Tamaulipas-Golden Lane-Chiapas fault zone (Pindell, 1985) or the East Mexico transform margin (Pindell and Kennan, 2009; and herein), is constrained in different ways along its length. North of Tuxpan, long-wavelength northwest-southeast trending continental anomalies are truncated by shorter wavelength north-south anomalies that accord with the seafloor spreading pattern. Southward from Tuxpan, the oceanic pattern persists to the coastline at 20°N, beyond which we infer the crustal boundary to continue down the axis of the Veracruz Basin to the west flank of the Mixtequita massif, which is probably a displaced portion of the Chiapas Massif. Overall, our tracing of the East Mexico transform margin is linear but has a kink that is marked on Figure 2 by blue dots along its middle section.

Observation 5

In the Perdido area, the boundary or juxtaposition between non-rectilinear (west and north) and rectilinear (east and south) magnetic pattern is especially apparent. This boundary mimics the western continuation of the NMAT.

Observations 6 and 7

Larger-than-normal displacements occur in both the NMAT and the SMAT in the central portion of the Gulf of Mexico. The displacement in the NMAT trends north-south and lies at about 27°N and 91.5°W, whereas that in the SMAT occurs at about 22.5°N and 94°W, and is northwest-trending.

Figure 3 shows three transects of total magnetic intensity derived from the aeromagnetic map. Transects A-B and C-D show that the three primary anomalies dominate the deep Gulf's oceanic domain. Note, however, the magnetic highs over the rifted continental crusts at the western and eastern ends of Transect C-D. The high at the western end is likely a southward extension of the Houston magnetic anomaly in Texas, and the high at the eastern end is the northern extension of the Campeche magnetic anomaly. Likewise, the easternmost high of Transect E-F is the southern end of the Campeche magnetic anomaly, and the high at the southern end of Transect A-B is also intracontinental. A plausible cause for these intra-continental magnetic highs is that they mark basalt bearing grabens within the rifted margins. We emphasise that the Houston, Campeche, and Florida magnetic anomalies lie landward of the continent-ocean transitions and therefore are unlikely to be sourced by classic seaward dipping reflector complexes.

Interpretation of the Aeromagnetic Map

We offer the following explanations for the origin and significance of the seven observed features noted above and shown on Figure 2.

Interpretation 1

The CMAT corresponds to the area of youngest oceanic crust in which the spreading center became extinct. This has been corroborated, in the west at least, by the gravity map and interpretation of Sandwell *et al.* (2014; Fig. 4). The crustal fabric recorded by the CMAT can be used to crudely estimate the paleo-position of the pole of rotation prior to the end of spreading. By fitting small circles to the extinct transform segments between the interpreted late ridge segments, and constructing small circle radii roughly parallel to the interpreted ridge segments, we derive a pole south of central Cuba (latitude 20.3°N, longitude 78.6°W) having a large error that we do not attempt to quantify due to the shortness of paleo-ridge and transform segments used. We judge that the CMAT spreading fabric extends north and south from the extinct ridge position by several tens of kilometers in the east and by some 180 km in the west (outlined by fine black dashed lines in Fig. 2), which amounts to an angular rotation of -5.6°. Note the implied precision of all rotation "data" herein derives from calculations only and should be disregarded.

This latest stage of seafloor spreading occurred about our "Pole 3." For convenience, we will refer below to the crust generated around a given pole as, for example, "Pole 3 crust." We will not yet address the age of initiation for this Pole 3 phase of spreading, but we agree with Martön and Buffler (1999) that spreading ceased at the end of the Berriasian (139 Ma), although the actual constraints on this proposed age allow for spreading to have continued into the Valanginian (139-134 Ma).

Interpretations 2 and 3

The NMAT and the SMAT lie just basinward of the estimated limits of autochthonous Callovian-Early Oxfordian salt on both sides of the basin (Hudec *et al.*, 2013; Pindell *et al.*, 2014). From this we infer that the basement beneath the two anomaly trends must be slightly younger, probably medial or Late Oxfordian. We test the likelihood of a genetic relationship between the NMAT and the SMAT by finding a pole of rotation that attempts to position the SMAT (assumed to represent Yucatán) onto the NMAT (assumed to represent North America). We initially found a surprisingly close fit and made minor adjustments on the order of 10-20 km in our final definitions of NMAT and SMAT to improve the fit to that shown in Figure 5. From the remarkable degree of overlap seen in Figure 5, we conclude that the two trends are rotationally displaced isochrons related to seafloor spreading. Figure 6 shows the position of Yucatán relative to North America if we accept plate rigidity in the two margins on which the two anomalies occur.

The rotation parameters for Figure 6 are latitude 22.7°N, longitude 84.1°W and an angular rotation of -30.5°. This pole is not the same as the pole determined above for the youngest crust around the CMAT. Furthermore, the SMAT is highly discordant with our CMAT pole. Thus, the pole of rotation must have shifted during the opening of the Gulf of Mexico, and our NMAT/SMAT pole and rotation must be a finite pole and rotation comprised of two or more stage poles and rotations, one of which is our CMAT pole and rotation.

Before determining additional stage pole(s) comprising the NMAT/SMAT finite pole, we first seek an explanation for the source of the NMAT and SMAT. Seismic sections (Fig. 7) show that both the NMAT and the SMAT are situated at the tops of the basement "step ups" (Pindell, 2002) to the Gulf's oceanic crust, which are also the outer flanks of sediment-filled outer marginal troughs (Pindell *et al.*, 2014). The outer marginal troughs correspond to the gravity lows rimming the eastern and the southern (Yucatán) deep Gulf of Mexico, consistent with their sedimentary, non-magmatic fill. By analogy with other magma-poor continent-ocean transitions around the world (Tucholke *et al.*, 2007; Perón-Pinvidic and Manatschal, 2010; Pindell *et al.*, 2014), the trough between the stretched continental and the oceanic crusts is likely floored by variably serpentinized, exhumed subcontinental mantle and possibly some stretched continental slivers.

If the outer marginal troughs in the eastern and southern Gulf are, as at other magma-poor margins, underlain by hyperextended crust and/or exhumed subcontinental mantle, then the basinward "shoulders" of the troughs as they rise to meet the flat-lying oceanic crustal surface are likely basement transition zones where igneous intrusion has occurred into serpentinized mantle during the onset of seafloor spreading (Perón-Pinvidic and Manatschal, 2010). Thus, this transition is considered here as a somewhat disorganised igneous interface between ocean crust and elevated mantle with probable variable width and abruptness. Such a transition might be expected to produce a magnetic "edge effect" that can give rise to margin-parallel magnetic anomalies. We currently favor this interpreted origin over other possibilities such as metasomatism of ultramafic minerals to magnetite in exhumed mantle. Another example of a margin-parallel, probable edge-effect magnetic anomaly at a magma-poor continent-ocean transition is the "S1 anomaly" off northwest Morocco (*Fig. 6c*; Maillard *et al.*, 2006). Note that the occurrence of autochthonous salt off northwest Morocco, just as in the Gulf of Mexico, is restricted to the landward side of the oceanic crust.

Both NMAT and SMAT are segmented by orthogonal interruptions, implying (1) the zone interpreted as hyperextended crust/exhumed mantle continued to stretch in a compartmentalised way as seafloor spreading began, or (2) which we prefer, that initial seafloor spreading magma chambers between this magma-poor pair of continent-ocean transitions were already compartmentalised and offset by transfer zones at the initiation of true spreading, much as at active spreading ridges today. This in turn implies that the plate kinematics of the rotational seafloor spreading had already been established during hyperextension/mantle exhumation.

From the above, the deep central Gulf's oceanic crust reaches the NMAT and SMAT, but continues no farther landward on either margin. We can now calculate stage pole(s) for the older portions of the oceanic crust that lie outside the younger belt of oceanic crust marked by the CMAT. Subtracting the CMAT stage pole and rotation from the NMAT/SMAT finite pole and rotation gives a candidate second stage pole and rotation for the NMAT/SMAT finite pole. We find that small circles around this stage pole fit the fabric of the NMAT, SMAT, and older belts of oceanic crust reasonably well. Thus, our model can be kept simple with the NMAT/SMAT finite pole being the sum of only two successive stage poles.

The proposal of two distinct stage poles for spreading in the Gulf of Mexico implies that a pole jump occurred during spreading, rather than a progressive pole migration. Our second stage pole lies at latitude 23.4°N, longitude 85.2°W and has an angular rotation of -24.9°. We shall refer to this earlier stage pole as Pole 2 in our model, and the two portions of older oceanic crust created by spreading about this pole will be called Pole 2 oceanic crust.

Interpretation 4

The "East Mexico Transform" separates continental from oceanic crust for a north-south distance of about 660 km, which is also the total amount of spreading in the westernmost Gulf (Fig. 4). Starting in the north, the structure runs slightly east of south (azimuth ~175°) from about 24°N/97°W to define the eastern, offshore flank of the Tamaulipas Arch/Burgos Basin, truncating the more northwest-trending magnetic patterns of that continental terrain. Along the eastern Tuxpan high, the structure acquires a north-south trend (between the two dots on Figs. 2 and 4), and the orthogonal oceanic spreading pattern of the CMAT lies in close proximity offshore, attesting to a very narrow, transform type of continental margin. Southward from Tuxpan, we interpret the structure to continue onshore at the easternmost tip of the Trans-Mexican Volcanic Belt. From there, we infer the trace of the transform to underlie the Veracruz Basin and ultimately to pass along the fault zone along the western edge of the Mixtequita massif, a primary basement dislocation separating differing basements (Salvador, 1987; Molina-Garza *et al.*, 1992; Pindell and Kennan, 2009). This requires the transform to acquire a trend that is east of south again, beyond the north-south kink that lies astride the CMAT.

From the above, we infer the existence of oceanic crust in the eastern Veracruz Basin. We also believe the oceanic crust continues onshore southward to the original northern limit of autochthonous salt deposition in the Salinas Basin, although this boundary has not yet been mapped. Such a trace for the East Mexico transform suggests that closure of the Gulf's oceanic crust should restore the Chiapas Massif to a position adjacent to the Tamaulipas Arch prior to spreading. Indeed, the Grenvillian, Permo-Triassic, and Paleozoic granites and meta-sediments of these two complexes are essentially indistinguishable in both age and geochemistry (Coombs, 2016).

Interpretation 5

The boundary between rectilinear and non-rectilinear magnetic patterns in the Perdido area is interpreted as the northwest flank of the westward extension of the NMAT, marking the boundary between oceanic and thinned continental crust. We suggest this is where the highly stretched lithosphere resulting from synrift extension is cut first by outer marginal detachments, followed by the onset of seafloor spreading at east-west spreading centers. In addition, as mentioned above, the conjugate to this pattern should lie in the basement along the northern limit of the salt-bearing Salinas and Campeche basins of southern Mexico. Although the magnetic map is less clear there, the overall magnetic pattern in the southwest Gulf seems consistent with the pattern expected for the early stage of seafloor spreading, as marked by the western continuation of the SMAT on Figure 2.

Interpretations 6 and 7

The larger-than-normal displacements within the NMAT and the SMAT are interpreted as marginal offsets remnant from the onset of seafloor spreading. They serve as control points in the along-strike parameter in the Oxfordian reconstruction of the otherwise curvilinear SMAT and NMAT.

Figure 8 schematically shows some geometric effects in the fracture zone pattern and the East Mexico transform that developed as a result of the pole jump during seafloor spreading. Figure 8A shows a hypothetical swath of ocean crust forming about an initial pole position and a single left-stepping transform in the active ridge system (such a transform step is responsible for observations 6 and 7, above). Figure 8B represents a later time and shows the separation of the two pre-existing halves of ocean crust about a different pole in a more southerly position. Note that on the northern side of the ridge system, the composite flow line around the early and later poles remains straighter than the flow line around the early pole alone.

Conversely, in the south, an angular or dog-leg relationship develops between the early and later transform segments. The younger pole's small circles must lead to one of two possible outcomes in the south: (1) Figure 8C, a new transform is cut into, or strong transpression shortens, the continental crust west of the original transform; or (2) Figure 8D, the continental block(s) west of the original transform is/are allowed to move laterally with a westward component so that the original transform remains the active site of displacement during the later pole's rotation (no new transform is cut). This is a form of strain partitioning in a three-plate system.

Concerning option one (Fig. 8C), we find no structure in Mexico's geology that could serve as a new transform about our younger stage pole. In contrast, option two (Fig. 8D) calls for continued block displacements south of Tuxpan during rotation about Pole 3. We believe that this speculation is justified in Mexico's geology, given the construction of deepwater troughs between the Valle San Luis, Tuxpan, and Cordoba shallow water platforms by Early Cretaceous time, which are presumably underlain by thicker, more buoyant continental crust (McFarlan and Silvio Menes, 1991). Furthermore, option two (Fig. 8D) predicts that the East Mexico transform should have a kink that pertains to the younger pole and to the crust generated around it. Such a kink is apparent in the magnetic pattern along eastern Tuxpan (two dots in Figs. 2 and 4).

Given the separation history of North and South America (Kneller *et al*., 2012; Pindell, 2014), the identification of the kink along the East Mexico transform, and the observation that extensional basement faulting continued across the Florida Straits through the Berriasian or into the Valanginian (Martön and Buffler, 1999), we consider that the jump in stage pole position (from the older Pole 2 to the younger Pole 3 oceanic crustal fabrics) is real, and suggest that it occurred within the Tithonian (152-145 Ma). Our tentative Tithonian reconstruction (Fig. 9; considered as 150 Ma) removes the Pole 3 oceanic crust within the fine dashed lines astride the extinct ridge position in Figure 2. It portrays the tectonic configuration of the Gulf during Tithonian source rock deposition, when deep water circulation remained blocked by the continental sills of the Florida Straits and southern Mexico (Pindell and Kennan, 2009) and the Gulf of Mexico was an isolated deep oceanic basin like the Black Sea. The Tithonian was also the time when most of the circum-Gulf basement highs were finally drowned and depositional settings became generally starved of local clastic input (Salvador, 1987; unpublished well data). For both and perhaps other reasons as well, source rock deposition was excellent at this time, forming a blanket across the oceanic crust that had formed by that time, as well as in the deep-water troughs between the nascent shallow water platforms across the Mexican onshore.

Continent-Ocean Transitions: Crustal Hyperextension and/or Exhumation of Subcontinental Mantle

More speculative is the period of crustal development just before the Oxfordian onset of seafloor spreading. The magnetic character to the north and south of NMAT and SMAT, respectively, is relatively subdued and of low intensity (Figs. 1 and 2). In the east and south, these zones correspond to the outer marginal troughs off Florida and Yucatán, where basement is demonstrably deep and such a situation presumably continues beneath the northern Gulf margin as well. We find that it is possible to make a reasonable conjugate reconstruction of these limits (green lines of Fig. 2) that follows the linear trends seen in the northern magnetic low, and we estimate a Bathonian age for this reconstruction (Fig. 10). This age is partly constrained by the Bathonian paleo-position of South America relative to North America (Kneller *et al*., 2012; Pindell, 2014) but is also dependent upon the choice of northern Andean reconstruction (*e.g*., Pindell, 1985; Pindell *et al*., 1998) and hence can only be estimated.

We define a pre-seafloor spreading stage pole relative to North America that moves Yucatán from our Bathonian/167 Ma to our Late Oxfordian/159 Ma reconstructions (latitude 26.7°N, longitude 84.8°W, angular rotation -17.5°). We can also determine a finite pole for Yucatán that restores it from today's position to the Bathonian position (latitude 24.1°N, longitude 84.8°W, rotation angle -48.0°). Seismic reflection studies (Pindell *et al.*, 2011; 2014; 2016; Goswami *et al.*, 2016) suggest that this Bathonian to Oxfordian phase of motion, which encompasses the period of salt deposition in the Gulf, was the time of hyperextension and/or mantle exhumation along most of the Gulf's margins, but not those of the southeastern Gulf, a transitional phase of tectonic extension between regional crustal rifting and true seafloor spreading referred to as "outer marginal collapse" by Pindell and Heyn (2011) and Pindell *et al.* (2014).

Synrift Crustal Extension

The Bathonian reconstruction (Fig. 10) places the Campeche magnetic anomaly parallel to and about 300 km southeast of the Houston magnetic anomaly; both anomalies lie in highly thinned continental crust. Early Central Atlantic opening history (Fig. 11; Pindell, 2014; Kneller *et al.*, 2012) indicates that 600-700 km of separation occurred between North and South America from Late Triassic to Bathonian time, the latter of which is the inferred age of our reconstruction. This separation is primarily achieved by intracontinental extension during the synrift phase, shared across the Venezuela-Yucatán rift zone, synrift expansion of Yucatán as a whole, and synrift extension across the U.S.-Yucatán rift zone (Salvador, 1991).

Judging from our Bathonian reconstruction (Fig. 10) and depending on how one might wish to conjugate the Yucatán and northern Gulf continental crusts (*i.e.*, pure shear, simple shear, *etc.*), the Houston and Campeche magnetic anomalies were probably on the order of 200 km closer to one another prior to rifting. Furthermore, they were probably parts of the same intracontinental rift zone, possibly a westward continuation of the Triassic-Early Jurassic Georgia embayment rift (Heffner, 2013). We decline to define a stage pole for Yucatán's synrift motion with respect to North America due to the uncertainty in defining a reference frame for margins and blocks undergoing extension. However, the northern Yucatán coastline and the Late Paleozoic Alleghanian-Marathon thrust belt would serve as relatively good proxies for the two margins.

An important point concerning magmatism and the onset of seafloor spreading in the Gulf margins is that although magmatism occurred during the synrift phase, there remains no documented observation of magmatic rock filling the outer marginal troughs along the circum-Gulf continent-ocean transitions (Imbert and Philippe, 2005; Pindell *et al.*, 2011; 2014; Pindell *et al.*, 2016; Goswami *et al.*, 2016). Thus, in terms of the standard means of classifying margins as magma poor or magma rich, namely the presence of seaward dipping reflectors spanning the continent-ocean transitions, we consider these margins to be magma poor at the time of continental break up. Globally speaking, margins may be magma rich during the synrift and magma poor during break up (Gulf of Mexico). Conversely, margins may be magma poor during initial rifting and magma rich during break up (Argentina).

Additional Points and Discussion

We summarize our stages of evolution and rotations of Yucatán relative to North America, going forward in time:

- Evolutionary Stage 1, generally believed to be the synrift stage, involving northwest-southeast intracontinental extension, proposed as Late Triassic to Middle Jurassic in age. No pole of rotation for Yucatán is given here.
- Evolutionary Stage 2, interpreted here as a period of post-rift hyperextension and/or subcontinental mantle exhumation within the continent-ocean transitions, and proposed as Bathonian to Early Oxfordian in age (167-159 Ma). Our first stage pole of rotation for Yucatán relative to North America (our Stage Pole 1) accords with this second kinematic stage (Evolutionary Stage 2).
- Evolutionary Stage 3, the earlier of two successive periods of true seafloor spreading, proposed as Oxfordian to Tithonian in age (159 to ~150 Ma). Our second stage pole of rotation for Yucatán relative to North America (our Stage Pole 2) accords with this third kinematic stage (Evolutionary Stage 3).
- Evolutionary Stage 4, the later of two successive periods of true seafloor spreading, proposed as Tithonian to the end of the Berriasian in age (~150 to ~139 Ma). Our third stage pole of rotation for Yucatán relative to North America (our Stage Pole 3) accords with this fourth kinematic stage (Evolutionary Stage 4).

To summarize, the rotation poles proposed herein for Yucatán relative to North America are:

- Finite pole to Oxfordian/159 Ma: latitude 22.7°N, longitude 84.1°W, angle -30.5°.
- Finite pole to Bathonian/167 Ma: latitude 24.1°N, longitude 84.8°W, angle -48.0°.
- Stage Pole 1, 167-159 Ma, latitude 26.7°N, longitude 84.8°W, angle -17.5°.
- Stage Pole 2, 159-150 Ma, latitude 23.4°N, longitude 85.2°W, angle -24.9°.
- Stage Pole 3, 150-139 Ma, latitude 20.3°N, longitude 78.6°W, angle -5.6°.

The curvilinear and orthogonal patterns observed in the magnetics of the deep Gulf pertain to Evolutionary Stages 3 and 4. They are interpreted as characterising typical oceanic crust, similar to and common throughout the world's oceans where near-pole rotational seafloor spreading fabrics are well mapped, for example the Cocos Plate (Mammericks and Klitgord, 1982) and the Bay of Biscay (Le Borgne et al., 1971).

Our three successive stage poles, defined relative to North America, show a southeastly jumping along the Florida-Bahamas Escarpment, ending up in the proto-Caribbean south of the Bahamas. This equates to rift propagation along the west Florida margin; furthermore, when Yucatán is restored to the Florida margin, it equates to rift propagation along northeast Yucatán as well, as it should.

Figure 11 relates our phases of Gulf evolution to progressive increments of the separation history between North and South America. The proposed timing for the transition to spreading in the Gulf (159 Ma) is significantly later than in the Central Atlantic (~190-195 Ma), due to much larger amounts of synrift intracontinental extension preceding spreading in the Gulf.

Figure 12 shows net flow paths of two points representing Yucatán with respect to North America, according to our reconstructions and several interpolations not discussed herein. The points for 195 Ma and 177 Ma are not strict representations for all of Yucatán, as the Yucatán Block was extending during those times. Note that the East Mexico transform lies significantly west of our travel path for Yucatán. This is because the Chiapas Massif was acquired as part of the Yucatán Block at 159 Ma when the nascent spreading/transform system cut the rifted continental crust across the basin into two halves. The Chiapas Massif ended up on the Yucatán side and hence travelled 660 km southward during seafloor spreading in the Gulf, having most likely originated along the eastern flank of the Tamaulipas Massif. In addition, assuming an Oxfordian-end Berriasian period of spreading (~20 Ma), the oceanic crustal accretion rate is ~36 km/Ma in the west and ~10 km/Ma in the east. No attempt has been made to correlate the magnetic anomalies in the Gulf with magnetic polarity reversals.

Figure 13 shows the crustal domains resulting from the four-stage history portrayed herein. The belt of youngest oceanic crust carries a risk of lacking part of the regional Tithonian source rock interval. However, Cretaceous source rocks should be omnipresent across the entire Gulf of Mexico. Figure 13 allows comparison of our proposed oceanic limit based on magnetics with that of the GUMBO refraction transects (G1, Van Avendonk *et al.*, 2015; G2, Eddy, 2014; G3, Eddy *et al.*, 2014; G4, Christeson *et al.*, 2014). The oceanic limit on G1, G3, and G4 agree quite well and probably within error, but no clear limit has been proposed for G2.

One concern with our model is that there is an apparent period of faster relative motion between North America and Yucatán between 167 and 159 Ma, when hyperextension, mantle exhumation, and salt deposition are inferred, before and after which separation was slower. This may be real, but other possible explanations for this may be that we have presumed too much hyperextended crust and/or exhumed mantle, and/or assigned an age for the reconstruction that is too young. If the former, our Bathonian map (Fig. 10) may show Yucatán slightly too far north. If the latter, our Bathonian map may be better considered as Bajocian. Such issues of interpolation where age control is poor or highly interpretive are always problematic in assessing paleogeography.

Relative to the aeromagnetic map, the Sandwell gravity image appears to have a longer wavelength signal such that certain fracture zones of our early Pole 2 oceanic crust can be incorrectly merged with those of our later Pole 3 oceanic crust. As explained by Figure 8, the two trends differ most in the southern Gulf (see merging of different fracture zone trends in Figs. 1 and 2). We consider that the two trends seen in the magnetics in the south, forming the dog-leg pattern, can be interpreted in the gravity image as a single, more tightly curved trend that approximates the dog-leg (*e.g.*, see the faint north-northwest trend in the gravity at latitude 21°/longitude 94.8° on Fig. 4). The result of merging the two trends is that a single pole may be proposed for forming all the Gulf's oceanic crust (*e.g.*, Nguyan and Mann, 2016), although a single pole may be less accurate than the two stage pole approach.

Since the completion of this work in 2014, the first author has had the privilege of mapping the basement and pre-salt units on the recent ION MexicoSPAN seismic reflection survey (Pindell *et al.*, 2016). In that work, along with further interpretation of the northern margin GulfSPAN and FloridaSPAN datasets, roughly 100 picks of the limit of oceanic crust around the Gulf have been mapped. We are pleased to report close agreement with the limit of oceanic crust presented herein (up to 50 km difference locally, but usually less). The local differences may owe to a variable degree of magmatic intrusion into the exhumed mantle such that the edge effect magnetic anomaly does not precisely match the reflection image's structure of the oceanic step up.

Conclusions

1. Of the three prominent magnetic anomaly trends on the aeromagnetic map, the Central magnetic anomaly trend (CMAT) is interpreted as the youngest oceanic crust and encompasses the Gulf's extinct spreading ridge. The northern and southern anomaly trends (NMAT and SMAT) correspond to the "oceanic step ups," or to the basinward flanks of the "outer marginal troughs," in the northern and southern Gulf. These trends have remarkably similar shapes and hence are interpreted as an Oxfordian isochron pair marking the start of the Gulf's spreading history.
2. The NMAT and SMAT are judged to occur at the interface between probable exhumed mantle (landward) and oceanic crust (seaward). We interpret the likely cause of the anomalies to be

an edge effect of the intrusive boundary between the oceanic rock and exhumed mantle, but an origin or an influence from metasomatic magnetite within the continent-ocean transition cannot be ruled out. In either case, the anomalies are consistent with the Gulf's margins being magma-poor at the time of continental break up (although there had been local synrift magmatism).

3. Late Triassic-Middle Jurassic synrift extension across the Gulf was directed northwest-southeast. Postrift hyperextension and/or mantle exhumation was rotational about our Stage Pole 1, followed by two distinct phases of rotational seafloor spreading about our Stage Poles 2 and 3 in the Florida Straits and proto-Caribbean. The three successive stages of rotation indicate a southeasterly jumping of Yucatán's pole of rotation relative to North America. This probably denotes rift propagation at the apex of the Gulf's spreading system.
4. We judge that seafloor spreading continued through the Berriasian and possibly into the Valanginia, and thus there is a risk that the very youngest crust lacks the otherwise regional Tithonian source rock section.
5. Assuming an Oxfordian to end Berriasian period of spreading (~20 Ma), the average oceanic crustal accretion rate is ~36 km/Ma in the west and ~10 km/Ma in the east, making the Gulf of Mexico's a slow spreading ridge system.

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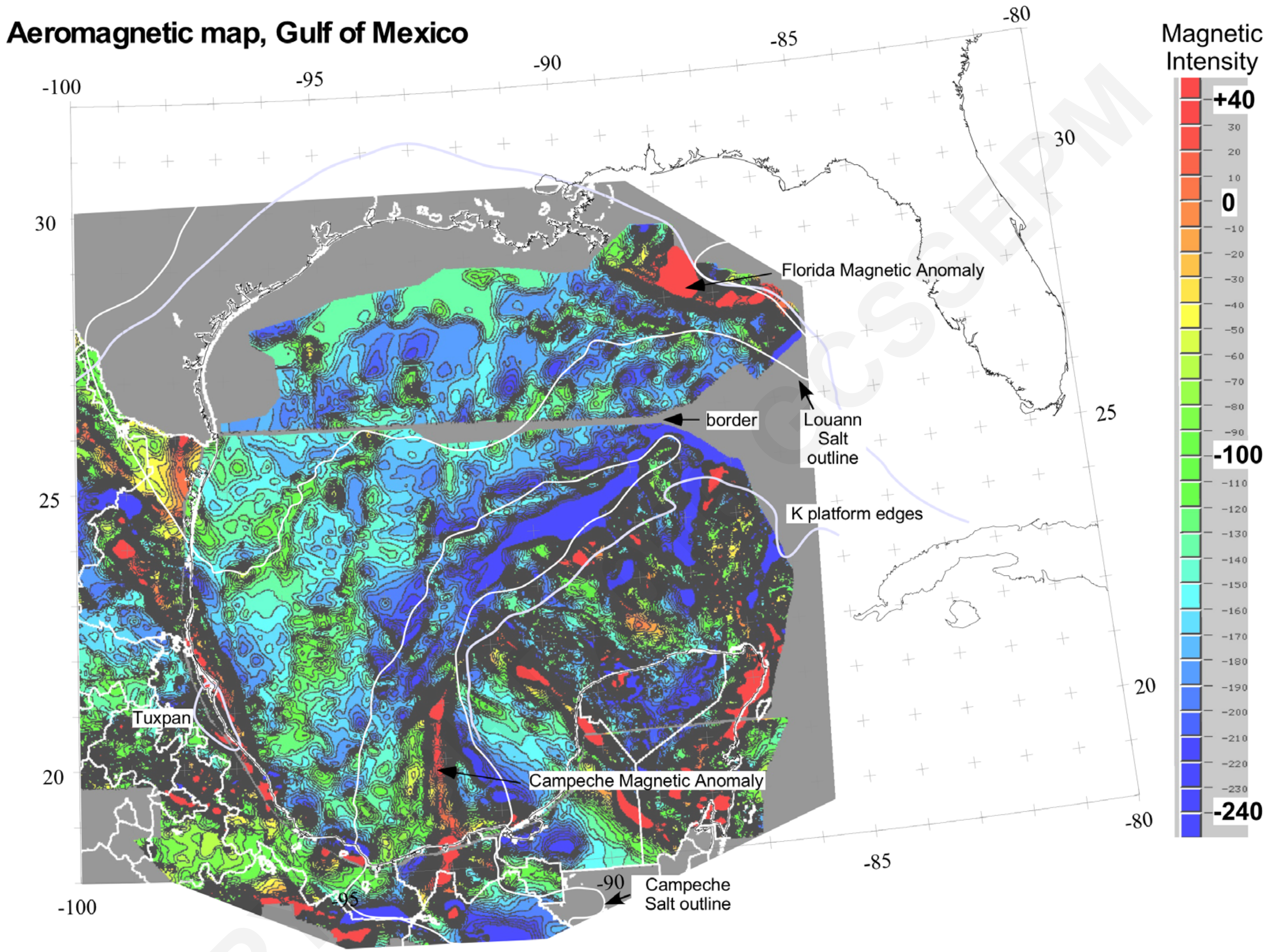

Figure 1. Reduced-to-pole, total magnetic intensity aeromagnetic map, scale given in nT, property of Pemex. Present day limits of Louann and Campeche salt and the Cretaceous shelf margins are shown for reference.

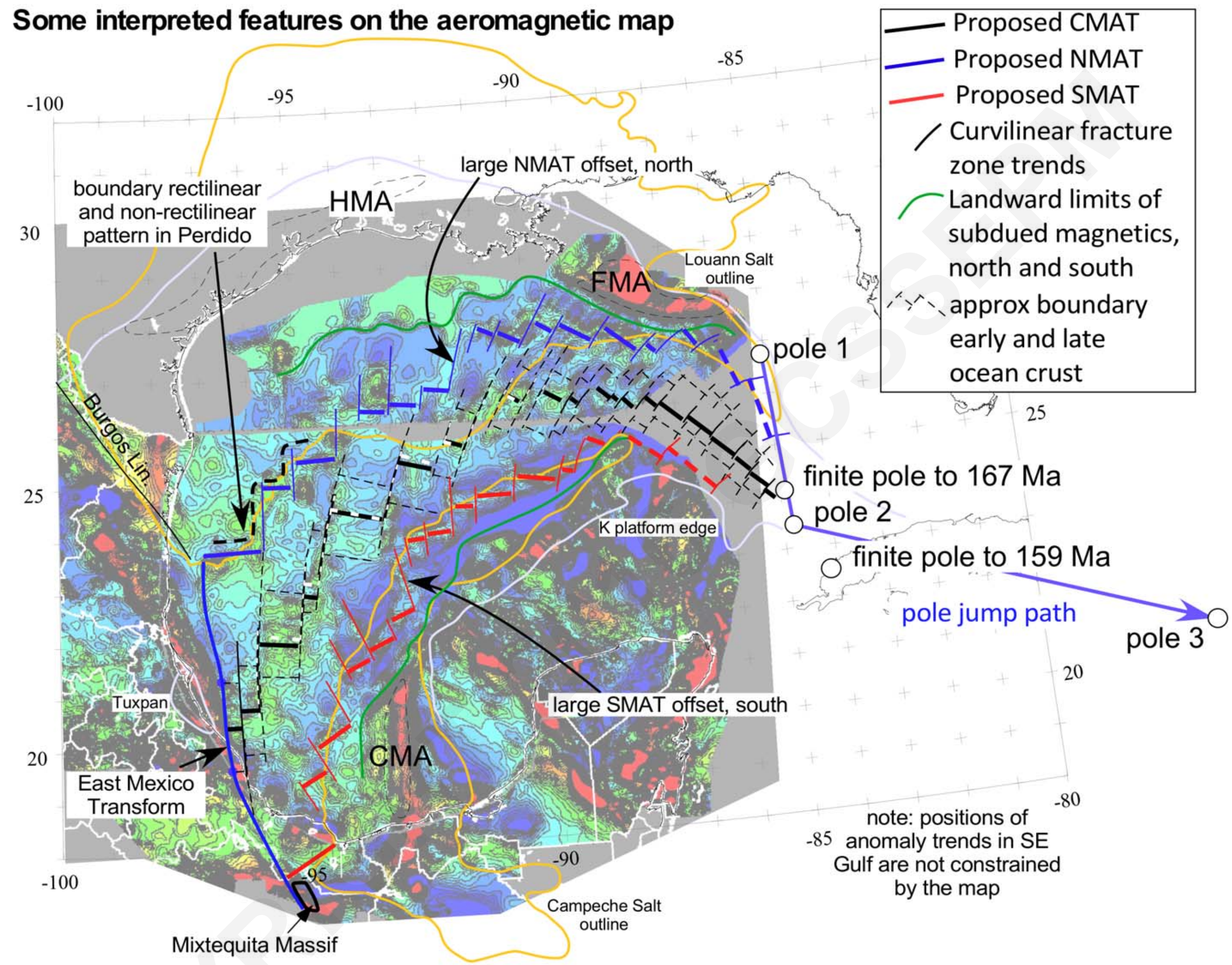

Figure 2. Seven features of the aeromagnetic map discussed in text, including the three primary magnetic anomaly trends (CMAT, NMAT, and SMAT) interpreted here as isochrons. Eastward continuations of the three anomaly trends beyond the data coverage are estimated and not constrained. Various poles of rotation discussed throughout the text are shown, along with the proposed jumps in the position of stage poles that sum to create the total finite poles given. The extinct spreading axis where visible in the vertical gravity gradient map (Sandwell *et al.*, 2014) is shown as the white dashes overlying the black CMAT lines. Background aeromagnetic image property of Pemex.

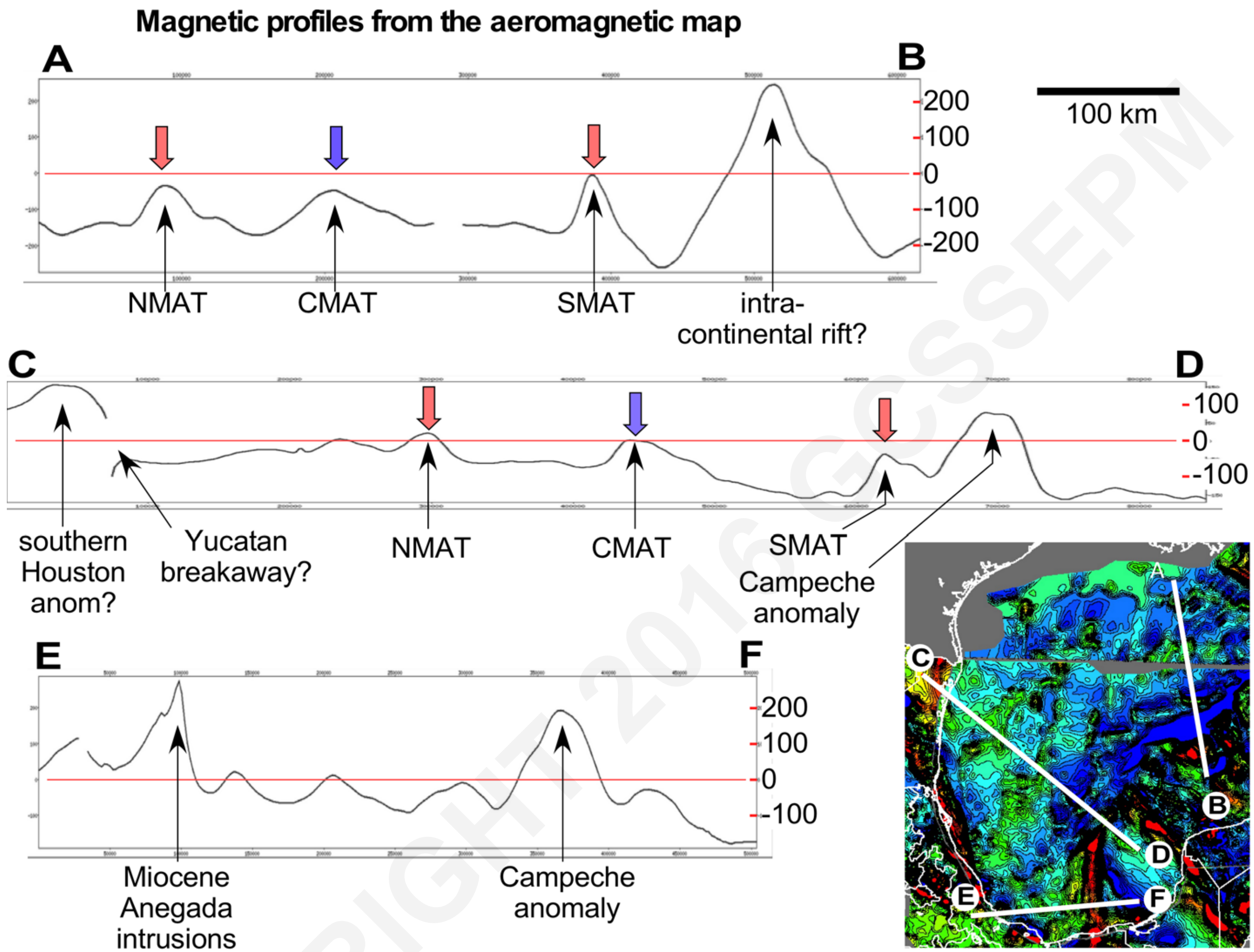

Figure 3. Cross-sectional profiles of total magnetic intensity from the map of Figure 1, scale given in nT. NMAT, SMAT, and CMAT are northern, southern and central magnetic anomaly trends, respectively.

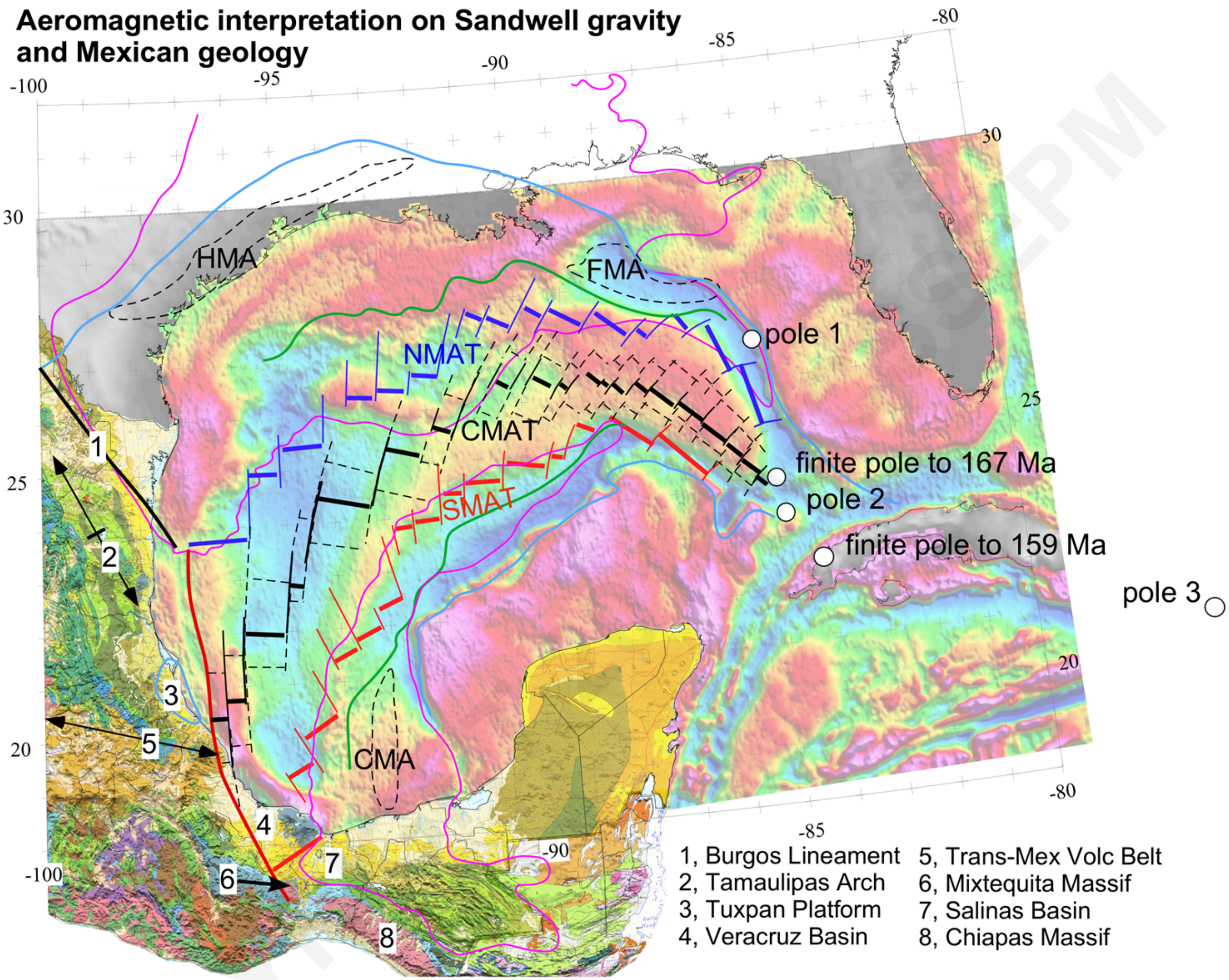

Figure 4. Merged color vertical gradient gravity map (Sandwell *et al.*, 2014) and onshore geology of eastern Mexico (Ortega-Gutierrez, 1992) and shaded topography (GTOPO30 digital elevation data) presented with primary interpretations herein, for comparison to Figure 2. Localities mentioned in text are shown.

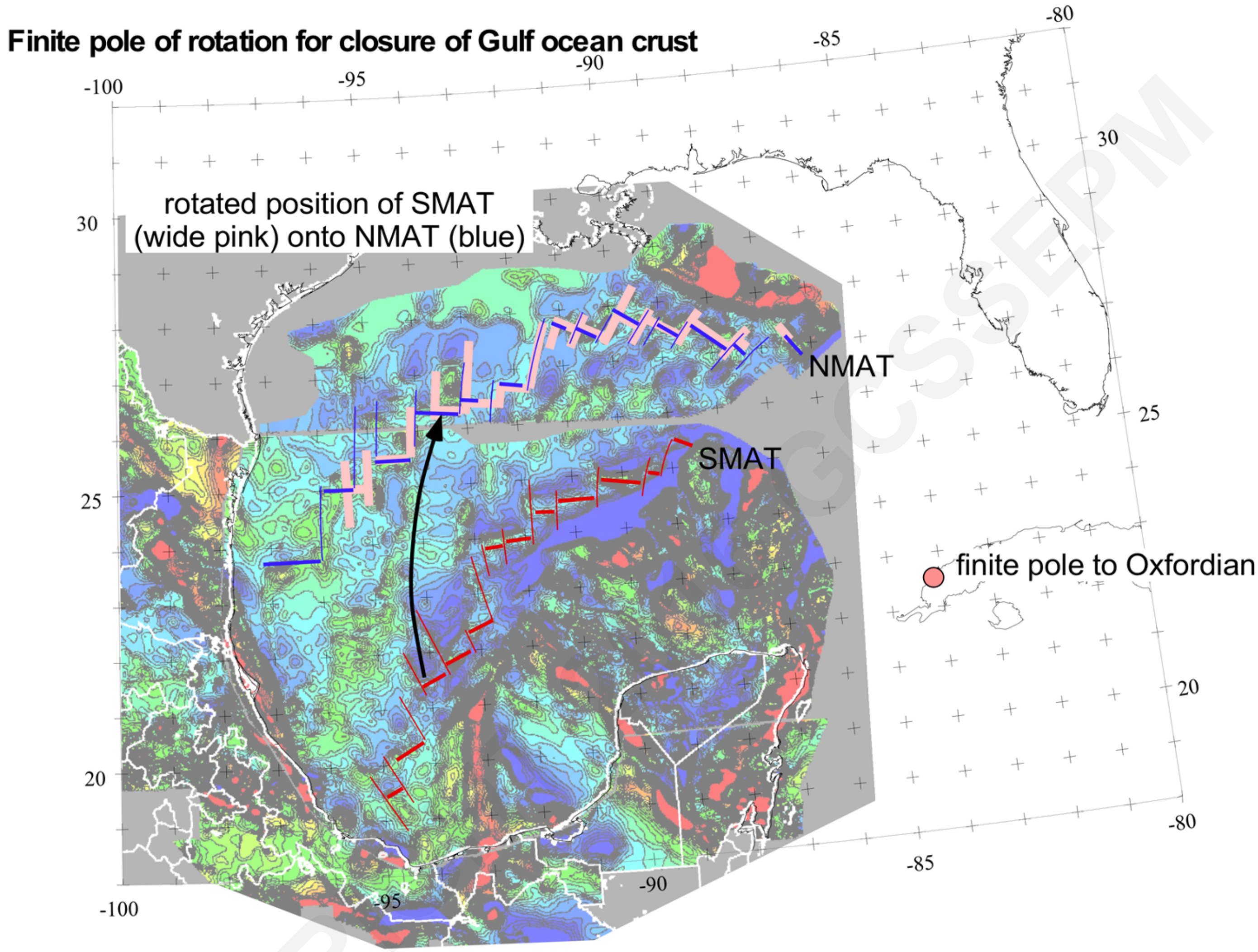

Figure 5. Reconstruction of SMAT onto NMAT, showing the remarkable map-view similarity of the two anomaly trends. The pole of rotation that achieves this overlay is the total finite pole to the Oxfordian in the Florida Straits (now the western Cuban coastline). Background magnetic image property of Pemex.

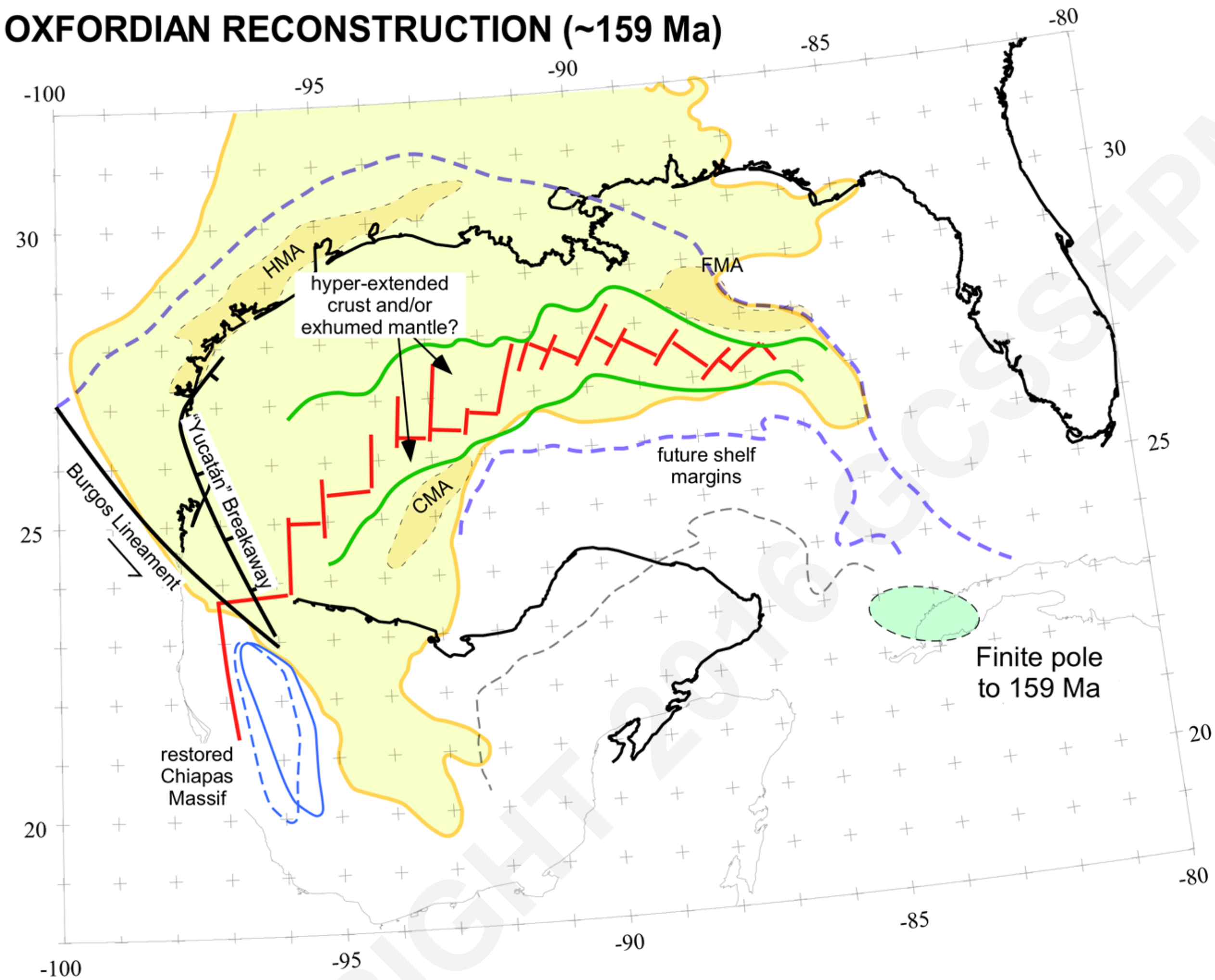

Figure 6. Proposed medial or Late Oxfordian (~159 Ma) plate reconstruction (assuming post-rift rigid plates) with Yucatán constrained by the analysis herein (SMAT and NMAT overlain). The autochthonous Louann and Campeche salt provinces are merged into one in this reconstruction; seafloor spreading is just beginning to separate them. The green lines define possible landward extents of hyperextended crust or exhumed mantle that are not "closed" in this reconstruction. The two positions for Chiapas massif are for the present (solid) and estimated for pre-Neogene shortening. HMA and CMA are Houston and Campeche magnetic anomalies, respectively.

The "oceanic step-up" appears to source the NMAT and SMAT

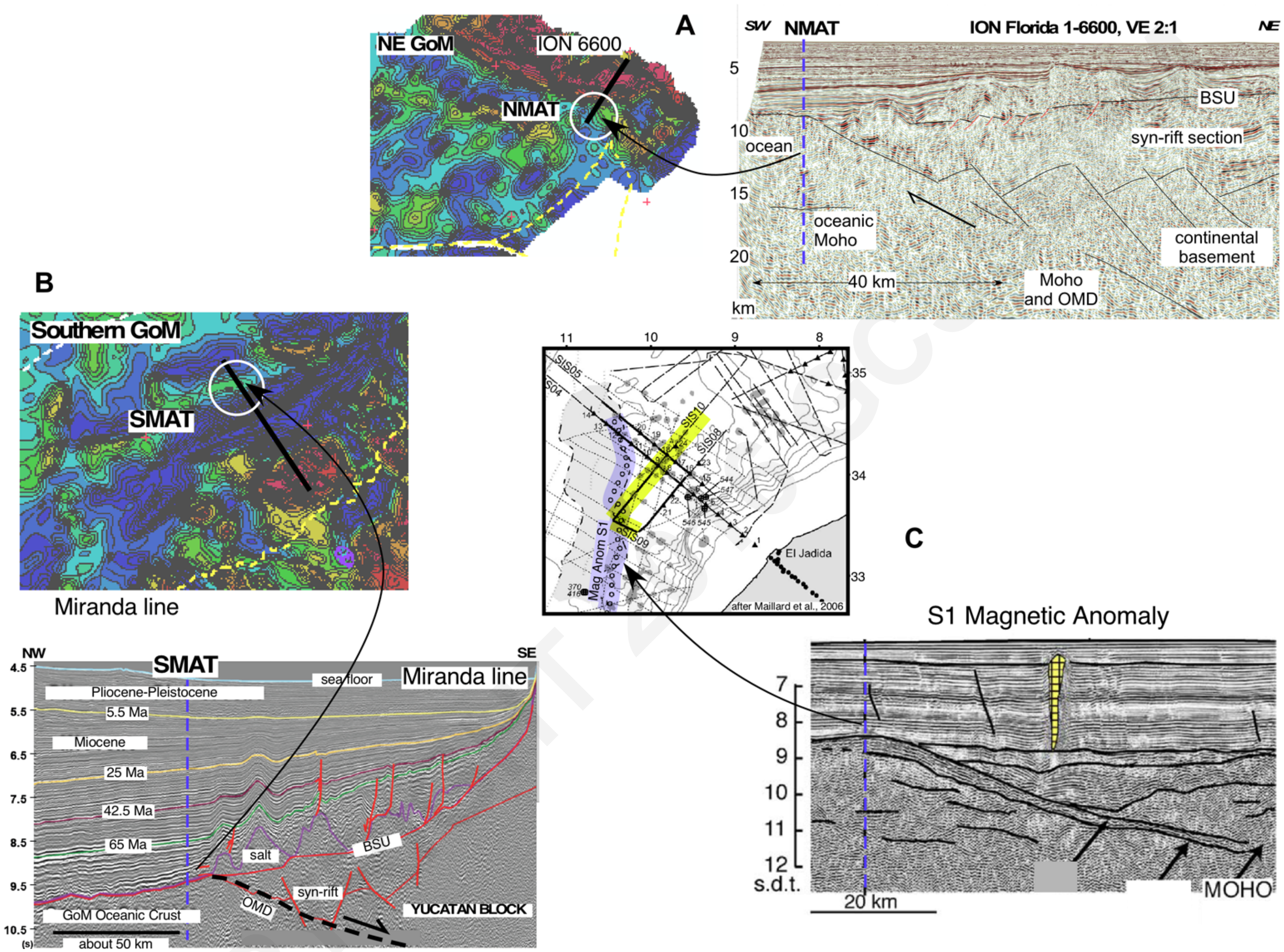

Figure 7. Seismic examples of the crustal position that appears to produce the margin parallel magnetic anomalies discussed in text. (A) NMAT (line from Pindell *et al.*, 2011); (B) SMAT (line from Miranda, 2011); (C) "S1" anomaly off Morocco (line from Maillard *et al.*, 2006), provided as an analog. We consider that the intrusive interface between the accreted oceanic crust and the exhumed subcontinental mantle causes an edge-effect magnetic anomaly.

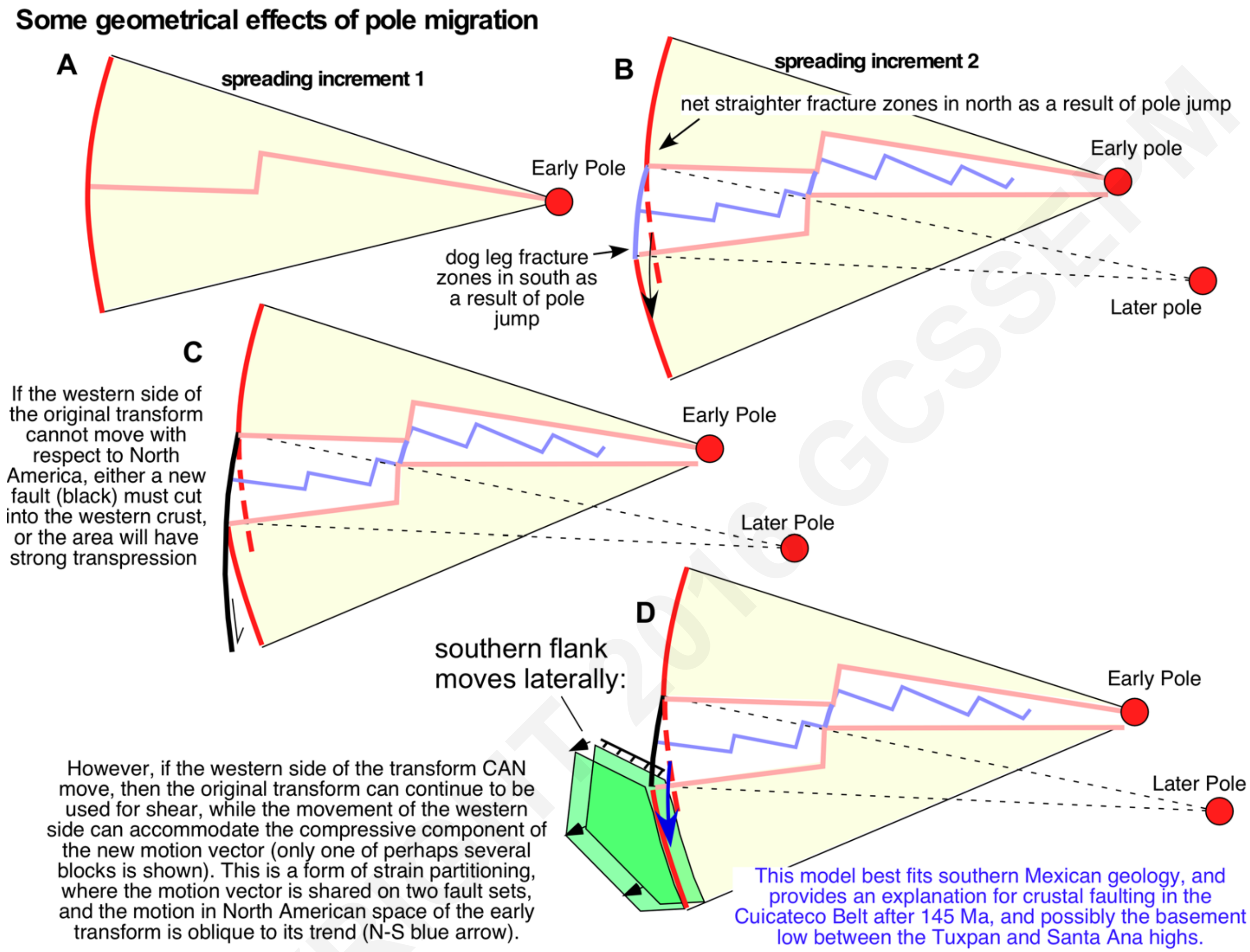

Figure 8. Schematic geometrical effects caused by jumps in the pole of rotation, as interpreted from the aeromagnetic map and applied to the Gulf of Mexico. See text for discussion.

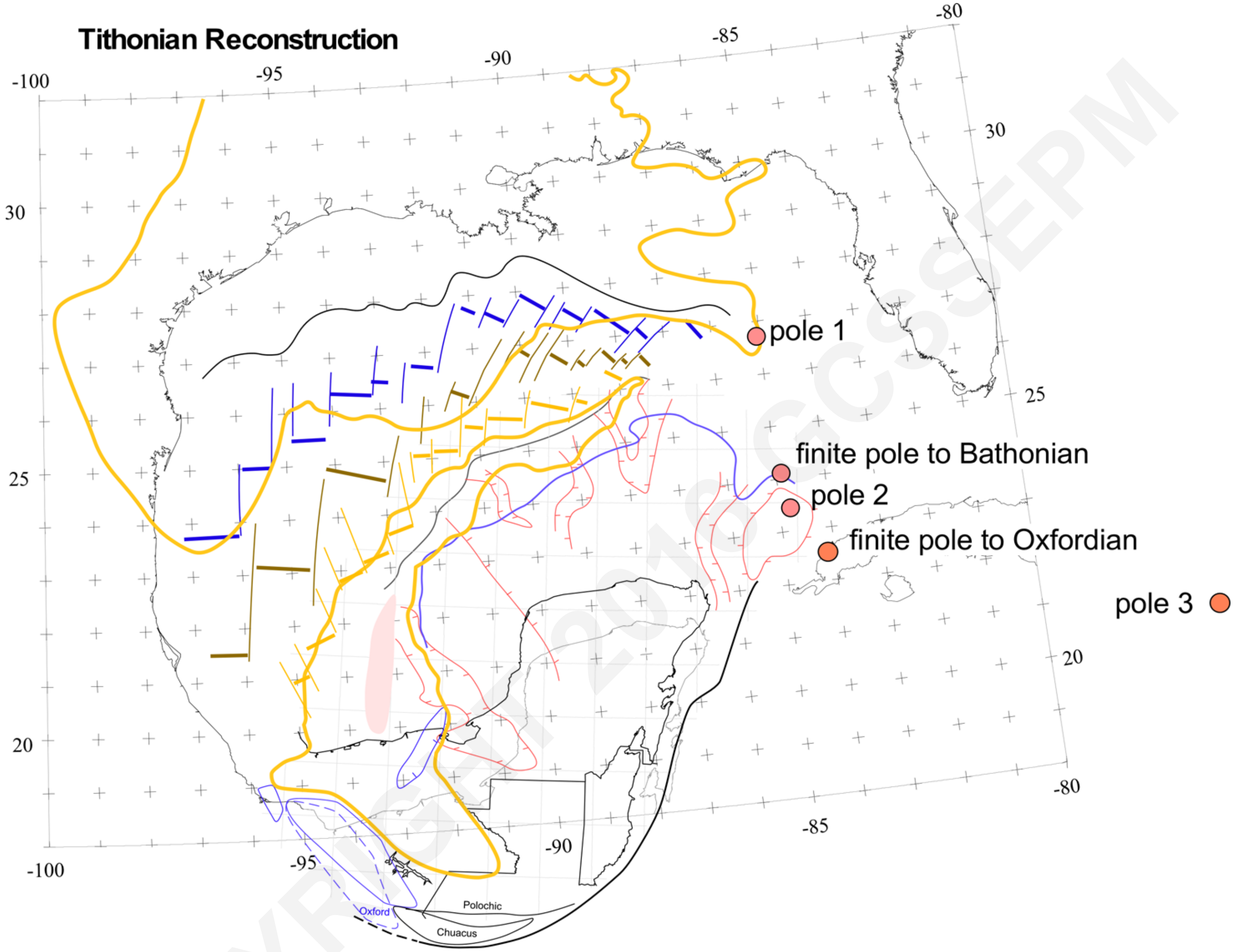

Figure 9. Proposed Tithonian (~150 Ma) plate reconstruction with Yucatán placed at the beginning of the Pole 3 spreading interval.

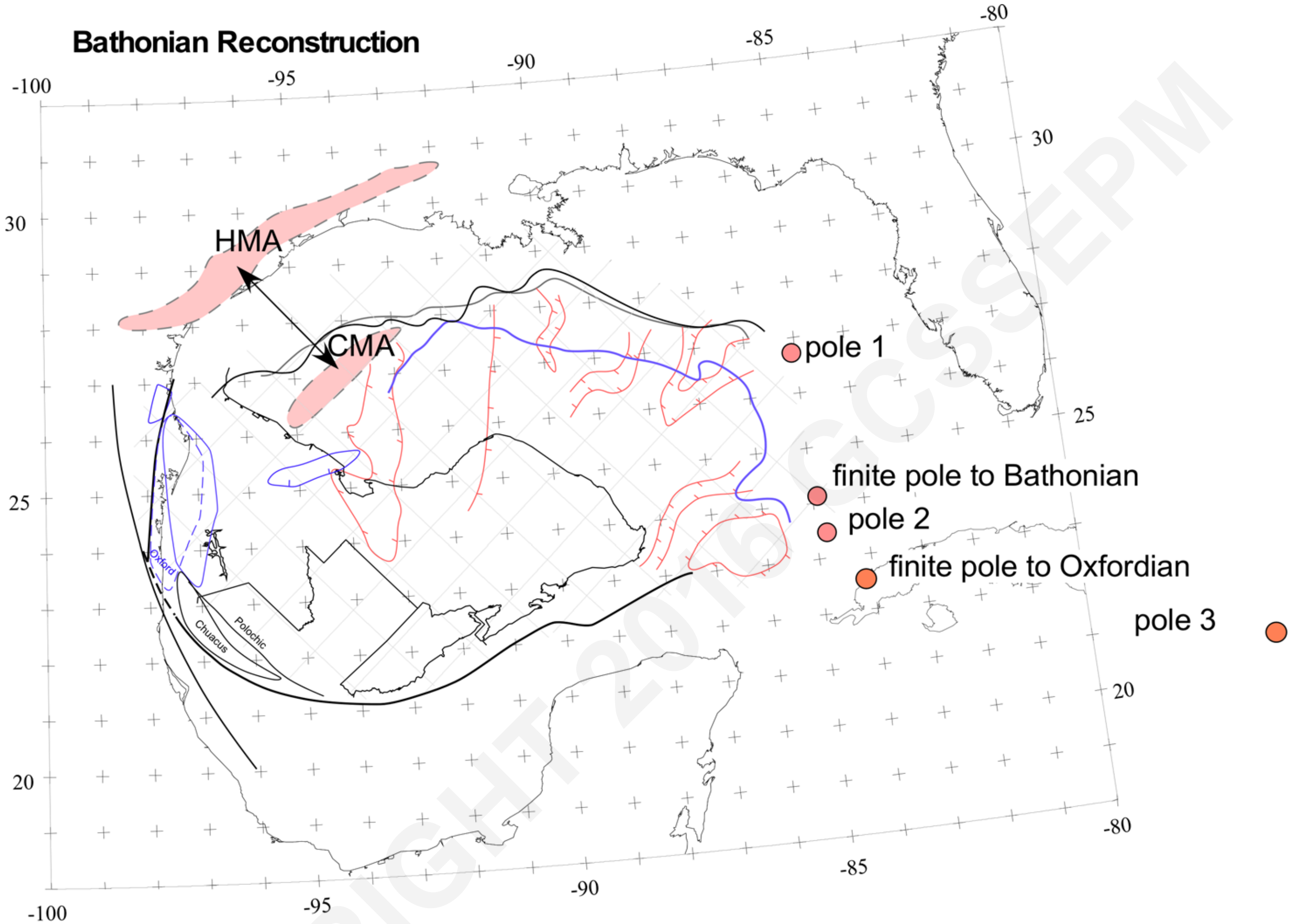

Figure 10. Proposed Bathonian (~167 Ma) plate reconstruction, prior to salt deposition. Yucatán is reconstructed to the landward limits of the low magnetic intensity areas that lie landward of NMAT and SMAT. HMA and CMA are Houston and Campeche magnetic anomalies, respectively.

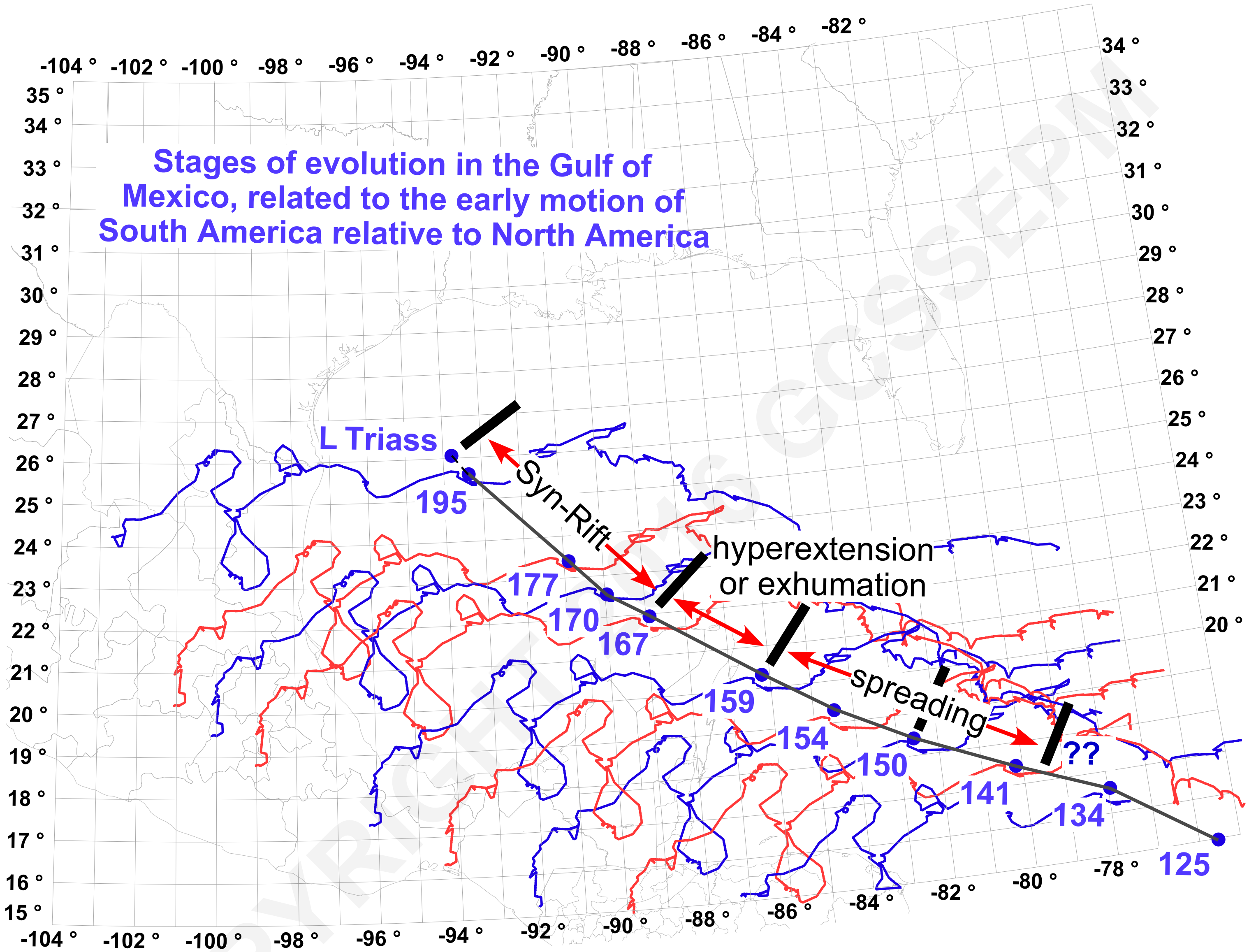

Figure 11. Relation of our proposed phases of Gulf evolution with the separation history between North and South America (modified after Pindell, 2014). The end of spreading in the Gulf is taken here as 139 Ma, but spreading could have continued into the Valanginian (up to 134 Ma). Note this is a slightly different projection than the maps in other figures.

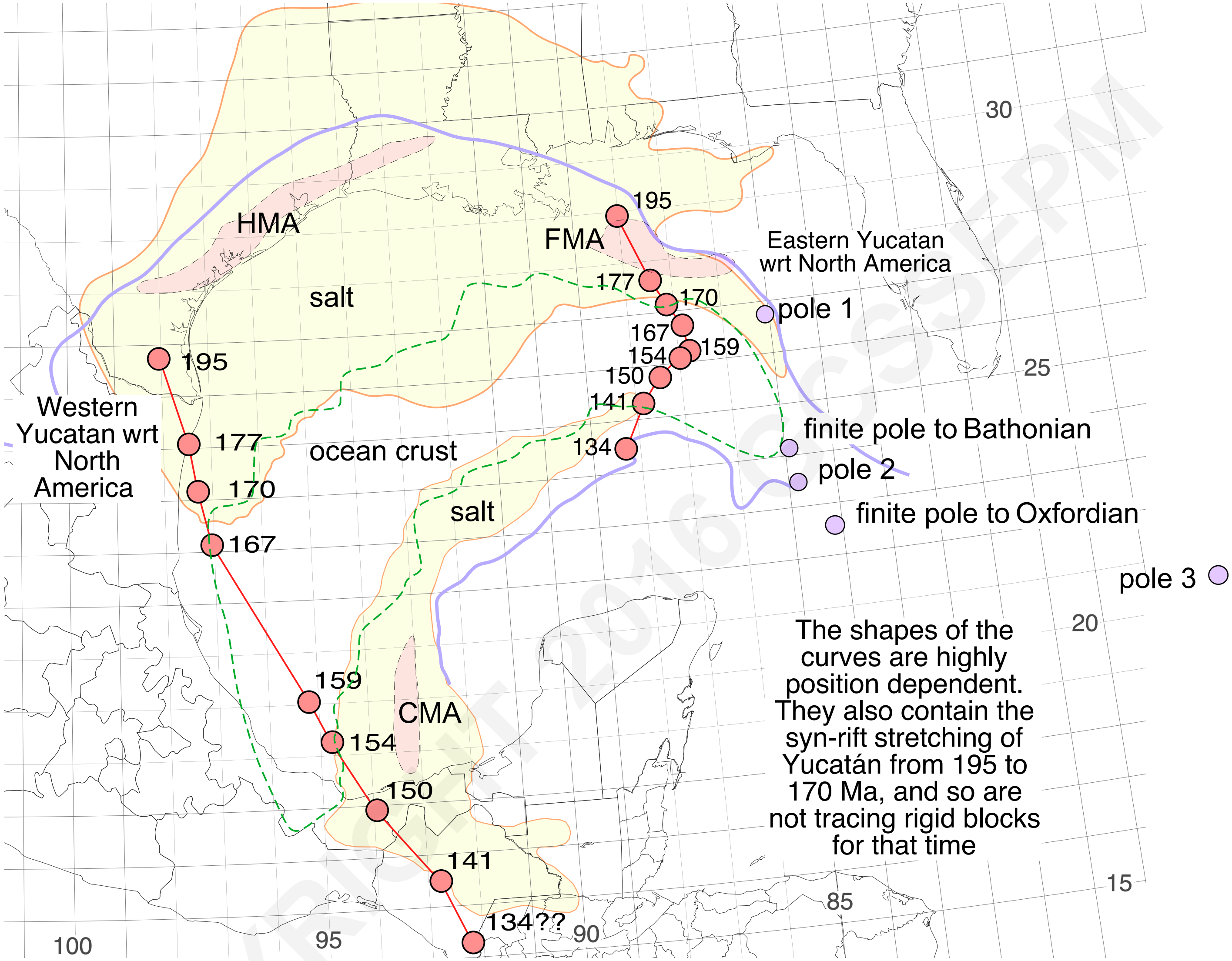

Figure 12. Flow paths of two points representing Yucatán relative to North America during the four stages of the Gulf of Mexico's tectonic development. The synrift encompassed northwest-southeast extension from Late Triassic through 167 Ma; hyperextension/exhumation of mantle spanned the period 167 Ma to 159 Ma; rotational seafloor spreading (in two substages) occurred from 159 to about 139 Ma. Positions of Yucatán through time are interpolated between diverging American continents (Fig. 11) and controlled by work herein along with regional geology.

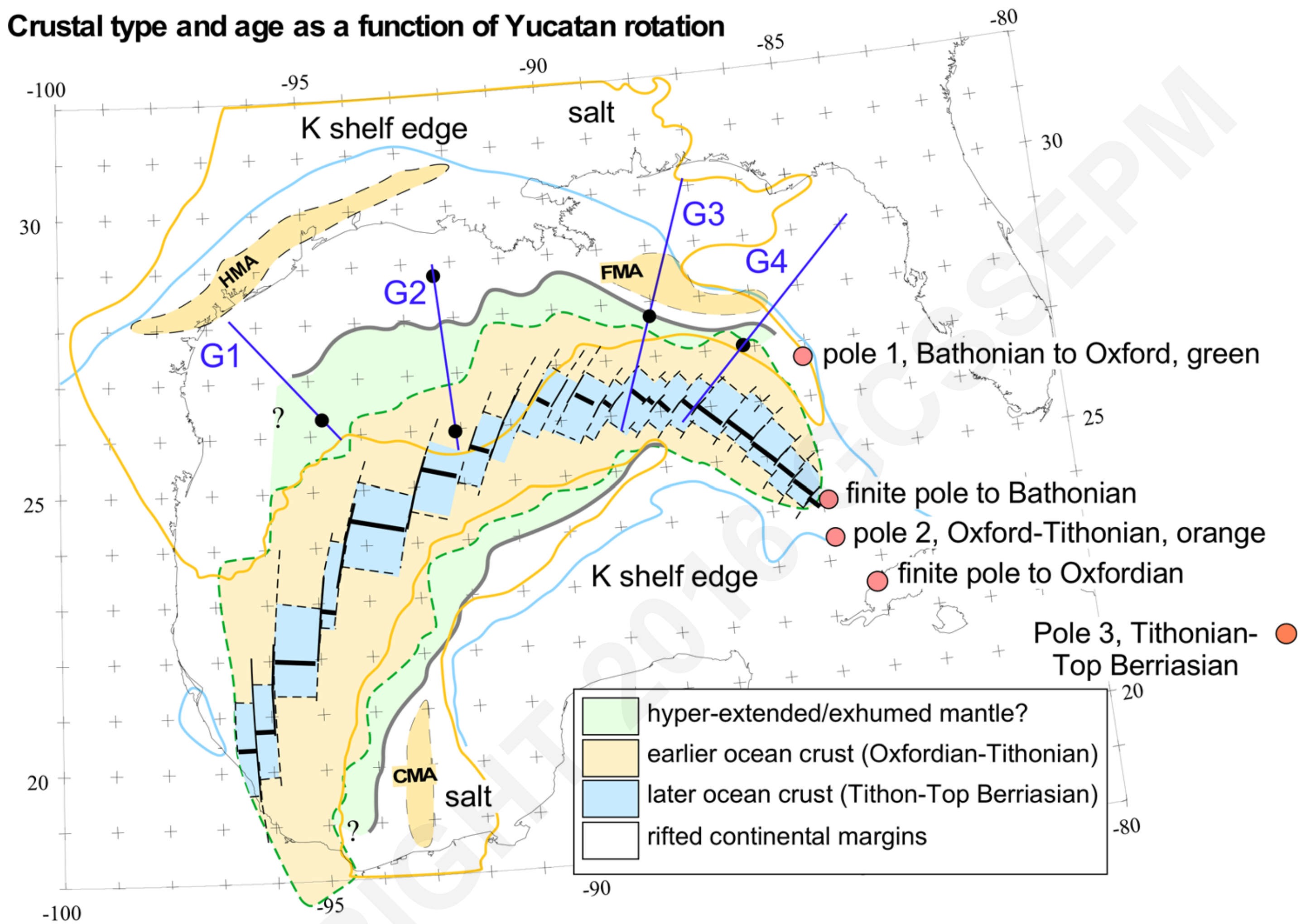

Figure 13. Map of four primary basement types (rifted continental, hyperextended/exhumed mantle, older (Pole 2) oceanic crust, and younger (Pole 3) oceanic crust. The four "G" transects are the GUMBO profiles; black dots show the interpreted limit of oceanic crust in those studies. G2 has two dots due to interpretational uncertainty.