

# **In-Situ Plate Tectonic Model of the Gulf of Mexico (GOM) and Caribbean Regions Using Elevation Grid as a Simple Tool for Kinematic Reconstruction of Plate Movements from Present Day to Pre-Breakup\***

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## **Introduction - Plate tectonic model and why is important for GOM and surrounds**

Whereas the plate tectonic model of the Gulf of Mexico (GOM) region is established with little difference between individual authors, the pre-Tertiary plate movement of the Caribbean is still hotly contended. As a result, two different models have been proposed:

- The Pacific model
- The in-situ model.

The Pacific model has been championed by Pindell since the 1980's (Pindell and Kennan, 2009; Pindell, 1985) and assumes the formation of most of the Caribbean in the Pacific region. This has been challenged by James (2005) who put forward an in-situ model where all present-day plates are the result of localised oceanic crust formation and relatively minimal movement of plates with respect to each other since the Permo-Triassic. This is important because the Caribbean extensional tectonics has a direct impact on the structural regime of the GOM region. Without understanding of the Caribbean region tectonic influence on GOM sediment input variations, onshore Mexico thrusting, gravity slides and finally halokinesis cannot be fully understood.

The Pacific Model:

1. Predicts creation of the Jamaica-Hispaniola-Cuba region as a volcanic arc in the middle of the Pacific during Early Cretaceous. If this is correct then ocean-ocean collision should be dominated by volcanic sediments with a complete lack of pre-rift Jurassic shallow marine sediments. This prediction, however, is inconsistent with observations of thick pre-rift non-marine sediments in Jamaica and in places in Cuba ([Figure 1](#)).
2. Predicts lack of Upper Jurassic source rocks within the Caribbean Plate. Source rock geochemistry of the Jurassic source rocks in Jamaica displays typical Jurassic Smackover to Haysville signatures (Cameron et al., 2004).
3. Predicts sediment of the Caribbean plate should be relatively thin as no significant land masses were attached to the region located in the Pacific. This prediction is again contradicted by Jamaica where sediment up to 20km has been encountered both onshore and

recently discovered offshore in the Walton Basin ([Figure 1](#)).

4. Predicts low chance of reservoir. This prediction is illustrated by Cuba but not by Jamaica, as Palaeocene to Eocene non-volcanic sandstones with a strong lithological similarity to the neighbouring Nicaraguan Rise has been intersected. In fact, the presence of Eocene sand-rich fans of the Wilcox Formation has been recognised as the principal reservoir deposited along the western edge of the GOM. Cuba's lack of post-Jurassic reservoir (if localised secondary carbonate porosity development is ignored) can also be successfully explained using an in-situ model.
5. No significant overburden and hence no seal and maturity.
6. Provides a complicated model that has no present-day equivalent.

All of the above points create a negative prospectivity perception with a lack of reservoir, source rocks and thick overburden that would not provide sufficient maturity for formation of hydrocarbons in this region.

In order to understand observational evidence of the Caribbean and hence a better understanding of the GOM's tectonic and depositional history, a series of plate constructions is presented here using an elevation "paper cut out method" to provide areal kinematic plate balance through time. To illustrate the strength of this approach, a staged removal of the oceanic crust from present day to the pre-Early Jurassic is presented in this section.

### **Present-day Setting and Comparison to Nova Scotia Sea**

The present-day tectonic setting is illustrated on top of an elevation grid in [Figure 2](#). The area extends from onshore Mexico and the US, includes GOM, Yucatan, Belize, Honduras, Nicaragua onshore and offshore, Cuba, Jamaica, Hispaniola, Puerto Rico, eastern edge of the Caribbean extending as far as Barbados, and shows the northern edge of South America. Understanding such a large area is necessary in unravelling the tectonic history of the GOM, and the immediate surrounding basins as this area has been affected by mostly extensional processes in the east and the corresponding, mainly compressional regime, in the west. The present-day tectonics illustrates a series of active and extinct spreading centres. Understanding the timing and direction of these centres is critical in understanding how the continental to mixed plates moved through time.

It is proposed that major clastic depositional rate increases are directly related to a limited space caused by extensional tectonics in the east and corresponding uplift and compression in the west ([Figure 3](#)). This statement may be counterintuitive as a Pacific plate subduction is continuously taking place along the whole extent of both American continents. The subduction process is a continuous event, and yet the central western part of onshore Mexico displays only local and time specific compression, suggesting that other significant processes are also contributing to limited space. Analysis of the mostly extensional plate tectonics in the Caribbean reveals specific times at which new oceanic crust was created and which coincide with periodic increases of sand sediment input into the GOM and other areas. The deposition of the highly prospective Wilcox Formation coincides with the onset of the Cayman Trough oceanic crust formation. This caused an increase in tensional stresses in the region and corresponding uplift of the hinterland, resulting in sand deposition in areas where space was available (GOM and eastern part of onshore Mexico).

In order to understand the tectonics of this region a comparison has been made to the Nova Scotia tectonic setting (Barker, 2011). A remarkable similarity is evident when gravity maps are compared of these two geographically distant regions ([Figure 4](#)). Whilst the southern Caribbean oceanic crust formation is still relatively unknown, the Scotia Sea spreading ridge is well illustrated by gravity, suggesting an in-situ spreading and enlargement of the area by a factor of four in the last 30 million years ([Figure 5](#)).

The analysis of the GOM DSDP (Legs 10 - Worzel et al., 1973, 77- Buffler et al., 1984), the Caribbean DSDP (sites 146 to 153), ODP (sites: 998B, 999B, 1000B and 1001A), available petroleum wells (Jablonski, 2008, Finder 2007 and Cameron et al., 2004), regional open-file seismic data (MGDS, 2016 ) combined with geochemical signatures of the volcanics (Chapin et al., 2004; Ferrari et al., 2005; Ferrari et al., 1999; DeCelles, 2004) and basement (Goldhammer and Johnson, 2001) has allowed a subdivision of this region into the oceanic and mainly continental areas. Once this has been achieved “time reversed” reconstruction using elevation image “cut-outs” has been undertaken. This approach minimises mistakes associated with maintaining areal balance, a common mistake during digital reconstructions. A series of plate reconstructions through time has been constructed; they also allow validation of main tectonic events.

The following main tectonic events that have a significant sedimentological impact on the GOM and surrounding areas have been identified:

- a. 10.5Ma late Miocene (Cuba<->Hispaniola/Puerto Rico separation);
- b. 55Ma early Eocene (Jamaica <-> Cuba/Hispaniola/Puerto Rico separation by formation of the Cayman Trough);
- c. 70Ma base Maastrichtian (Yucatan/Belize/Honduras/Nicaragua <-> Jamaica/Cuba/Hispaniola/Puerto Rico separation and formation of the Yucatan Basin);
- d. 94Ma Turonian (North America <-> South America separation and formation of the Southern Caribbean Basin);
- e. 180-145Ma Early Jurassic to Tithonian (formation of GOM, Mexico/Yucatan<-> Florida/US separation and formation of the north Atlantic plate); and
- f. Before 180Ma the Permo-Triassic setting (intra-cratonic mainly non-marine basins).

Unlike most of the studies, the following discussion will outline the collapse of the region in a similar fashion to the Scotia Sea expansion.

Despite a significant amount of work done to date, it also should be noted that an integrated study of the Mexico, US and Caribbean that combines volcanic analysis, basement age and chemistry, heavy mineral analysis, chemostratigraphy, sequence stratigraphic analysis of geographically distant basins is still lacking. Such a study would have beneficial results for evaluating areas that are not only well known areas but have also been traditionally discounted in terms of hydrocarbon prospectivity.

### **10.5 Ma Basal Late Miocene Plate Reconstruction (Cuba<->Hispaniola/Puerto Rico Separation)**

The late Miocene plate reconstruction has been created by cutting out the 10.5 million years to present-day oceanic crust generated in the Cayman Trough. A removal of a relatively small amount of oceanic crust allows Hispaniola and Puerto Rico to be connected to the southern edge of Cuba with areal balance maintained (Mann, 2007; [Figure 6](#)).

When Hispaniola/Puerto Rico separated from the southern edge of Cuba this caused an increase in tensional stresses in the GOM and resulted in the onset of gravity slides along the eastern edge of Mexico. Continuous expansion of the Cayman Trough also caused the halokinesis of Callovian salt. This combined with gravity slides created widespread salt canopies in the Saline-Campeche areas, offshore Burgos and the US part of the GOM. The present-day distribution of salt gives a clue to the early spreading history of the basin and is used in the cut-out method to argue the location of the spreading centre and amount of oceanic crust created in the GOM (see [Figure 10](#)).

### **55Ma Early Eocene Plate Reconstruction (Jamaica <-> Cuba/Hispaniola/Puerto Rico Separation by Formation of the Cayman Trough)**

The 55Ma event corresponds to the onset of the widespread deposition of the highly prospective Upper Wilcox Formation. The depositional trigger for this sequence was caused by the formation of the first oceanic crust in the newly forming Cayman Trough and corresponding separation of Jamaica from the Cuba, Hispaniola and Puerto Rico microplate ([Figure 7](#)). The onset of the Cayman Trough spreading onshore Mexico experienced additional compressional stress that resulted in the Laramide Uplift (Alzaga et al., 2009), onset of prograding thrust fronts and development of erosional Chincotepec paleochannel (canyon) in front of the elevated area (Pemex, 2013).

### **70Ma Maastrichtian Plate Reconstruction (Separation of Cuba Complex from Nicaraguan Rise and Yucatan Platform)**

This reconstruction was created by the removal of the oceanic crust within the present-day Yucatan Basin, which combines the Cuba microplate complex with the Nicaraguan Rise (Saura et al., 2008; [Figure 8](#)).

The onset of the new oceanic crust, interpreted to be of the Maastrichtian age, has resulted in an uplift of present-day onshore Mexico and progradation of the Sierra Madre Oriental Thrust Front and corresponding deposition of the clastic wedges adjacent to the compression. As the new Yucatan Basin formed, a renewed compression caused volcanic arc activity at the northern edge of Cuba and eastern rotation of the area to its present-day location.

### **94Ma to 70Ma Turonian to Campanian Plate Reconstruction (Separation of North and South America Plates and Formation of the Southern Caribbean Basin)**

A vast mostly deep water area located between Nicaraguan Rise-Puerto Rico edge, a chain of small islands in the east and the northern edge of South America, has been interpreted to be mostly underlain by the oceanic crust of the Turonian to Campanian age (Giunta et al., 2003). [Figure 9](#) illustrates the removed oceanic crust of the Southern Caribbean Basin, resulting in the connection of the Nicaraguan Rise, Jamaica, Dominican Republic and Puerto Rico with South America (Colombia and Venezuela). Highly prospective Maracaibo Basin is connected with Jurassic and Cretaceous depocentres discovered in the Jamaican region (Jablonski, 2008). This interpretation vastly differs with the Pacific plate tectonic model which assumes the formation of Jamaica thousands of kilometres east of its current location. Searcher's significant in-house knowledge on the DSDP, ODP, petroleum wells and seismic data indicates that the in-situ model is plausible and satisfactorily explains why in the middle of the Caribbean plate a significant depositional thick centre exists in Jamaica ([Figure 1](#)).

It should be noted that volcanic activity in Jamaica possibly commenced as far back as the Berriasian, suggesting that early movement perhaps associated with the creation of Lower Cretaceous oceanic crust should not be discounted. If this is the case, then the cessation of spreading at the end of the Tithonian in the GOM has been offset by the creation of a new spreading centre in the Caribbean. Future deep-ocean drilling located in the Southern Caribbean Basin should be able to test this theory.

### **155Ma-145Ma Oxfordian to Tithonian (GOM Oceanic Crust)**

Despite an excellent gravity and magnetic data base, the age of the GOM oceanic crust can only be deduced from its effects on sedimentation. Various models have been proposed with various oceanic-spreading timing and directions (e.g., Hudec et al. 2013; Pindell et al., 2009; James, 2006; Jacques et al., 2004). This study builds on the in-situ model developed in the neighbouring Caribbean Plate and proposes a similar elevation “cut-out” based reconstruction ([Figure 10](#)).

The Campeche-Saline-Reforma-Mucuspana basins have been separated from the Burgos-Veracruz area with the salt edge providing a clue as to the amount of GOM extension in the Late Jurassic. The direction of stretching is indicated by the NW-SE orientation of the Tamaulipas-Oaxaca transform. The GOM never fully opened, and during significant geological periods restricted oceanic conditions persisted, generating a number of source rock intervals from the Late Jurassic to Miocene.

### **Early Jurassic to Callovian Plate Reconstruction**

The onset of the timing can be deduced from the onset of the Early Jurassic clastic deposition and our understanding of the first oceanic-crust generation between Eurasian and North American plates (Veevers and Powell, 1994; Condie, 1989; Ross and Scotese, 1988). As a result of this distant rifting process, the GOM has only partially opened, creating ideal conditions for deposition of Callovian evaporites. Note that a similar intra-cratonic basin also existed between the central Caribbean and present-day northern edge of South America. This would explain why pre-breakup evaporites also exist in Jamaica and Cuba ([Figure 11](#)).

### **Pre-Early Jurassic Plate Reconstruction (Permo-Triassic and Older)**

This interval is still poorly understood (Whitmeyer and Karlstrom, 2007; Torres et al., 1999; Salvador, 1987). The onshore Mexico basin contains non-marine sediments deposited in the intra-cratonic setting. The presence of deeper oceanic conditions SW of present-day Mexico is inferred from the onshore sediments outcrop in the area (Bartok, 1993), with the presence of the oceanic plate unknown ([Figure 12](#)).

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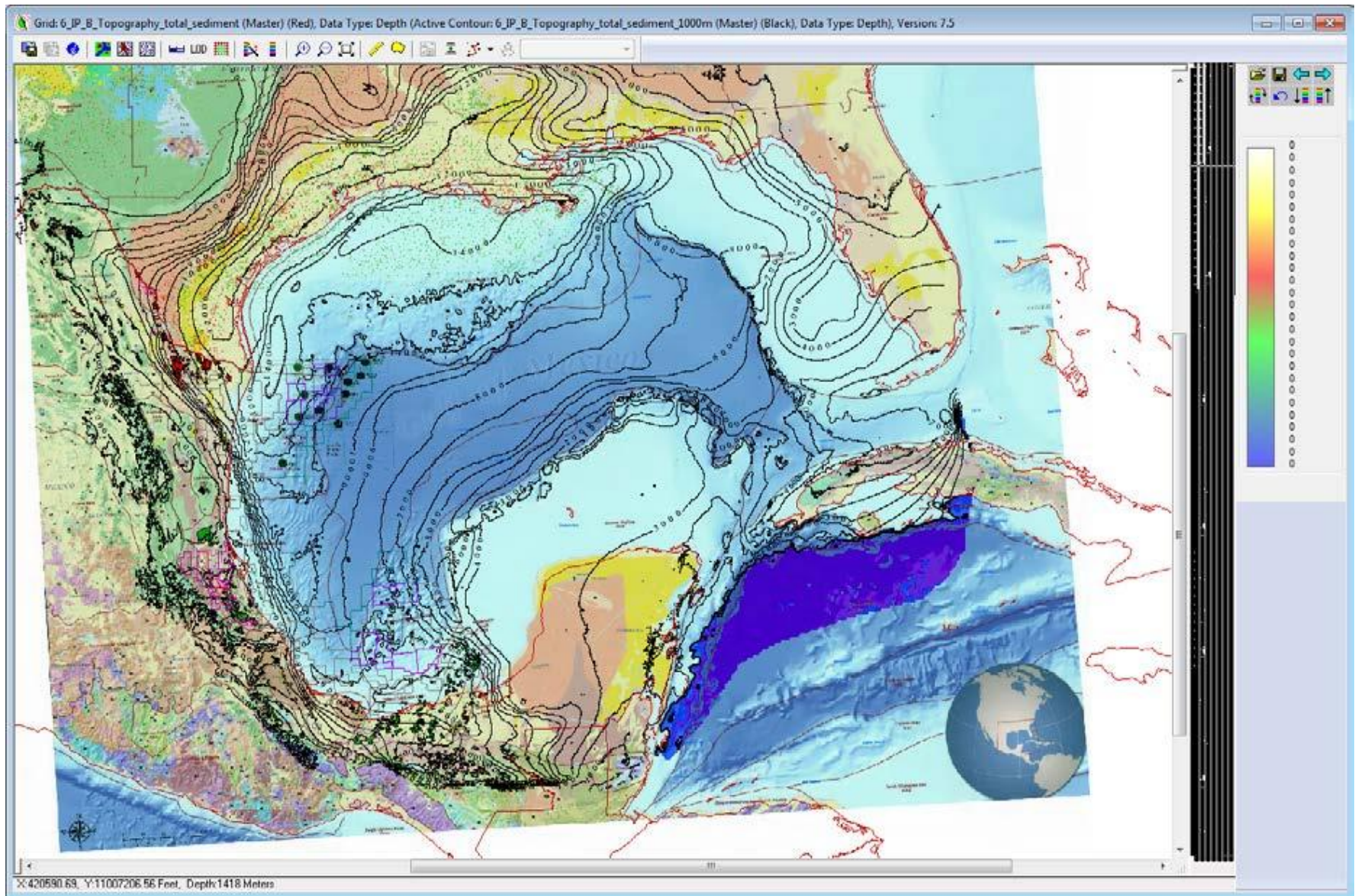


Figure 1. Sediment thickness in metres (sourced from NOAA; 2016; Galloway, 2008; Jablonski, 2008).



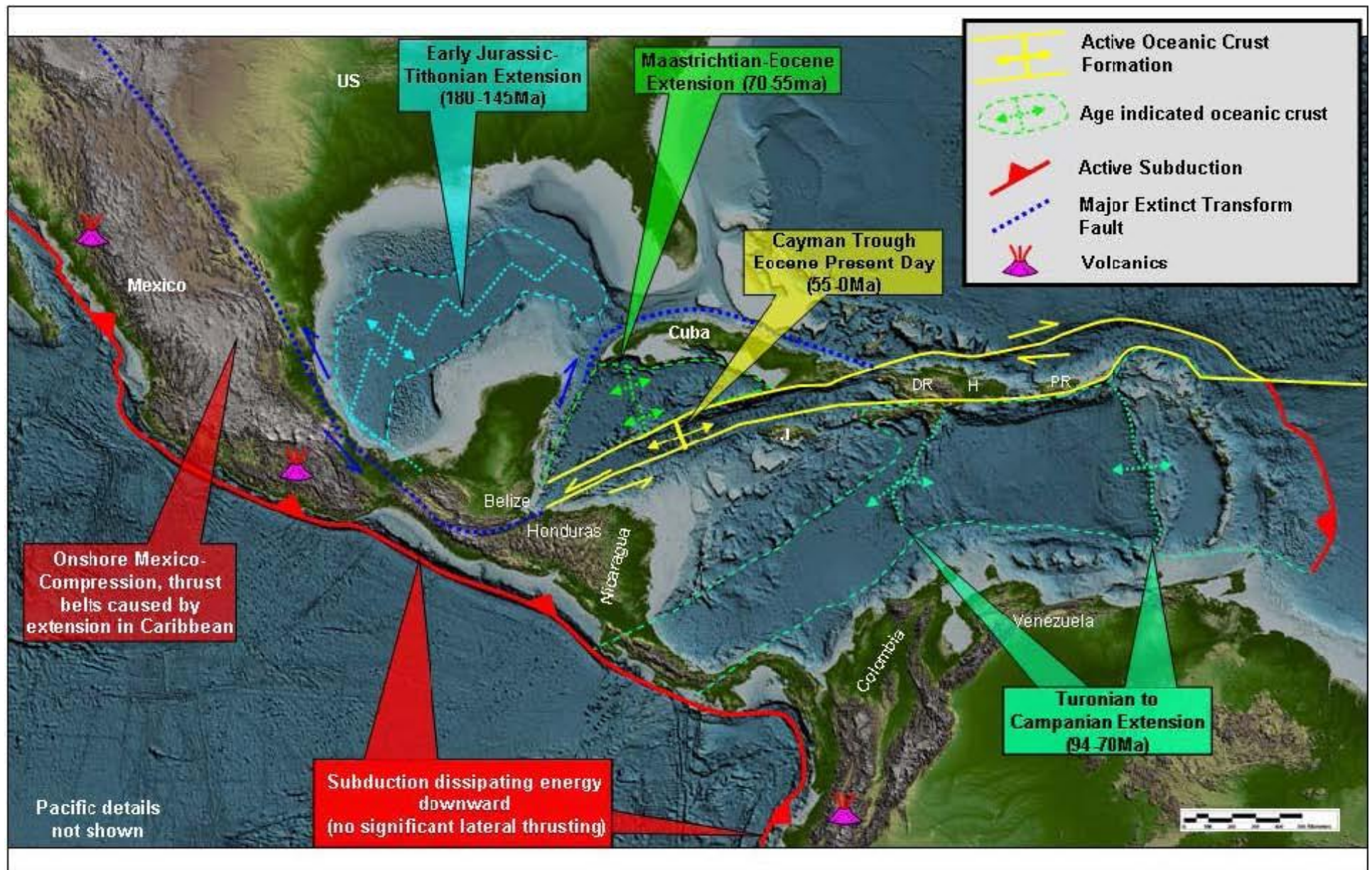


Figure 2. GOM and Caribbean present-day tectonic setting.

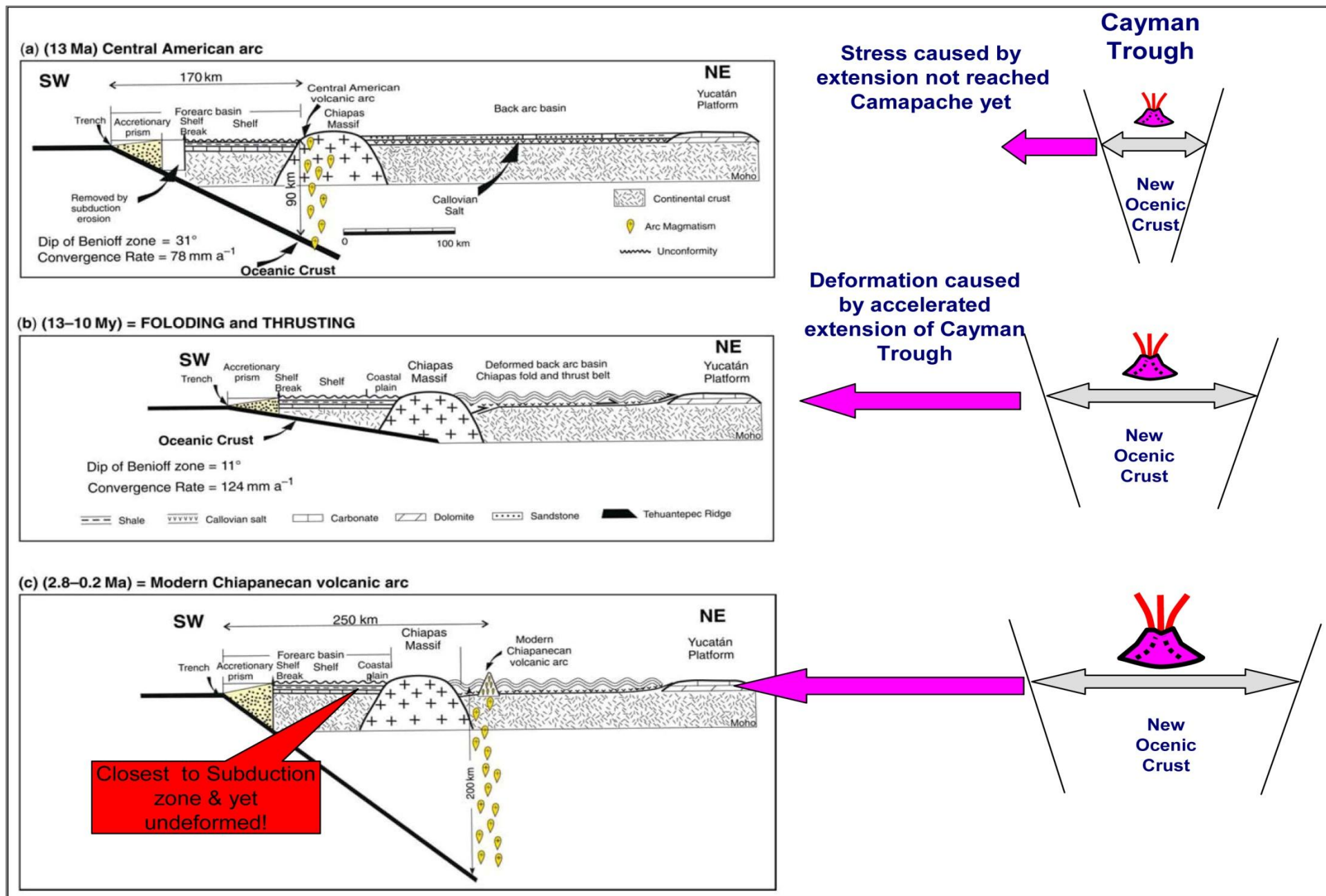


Figure 3. Tectonic evolution of Chiapas and Campeche region controlled by extension of the Cayman Trough, not by subduction as suggested by Mandujano-Velazquez and Keppie (2011).



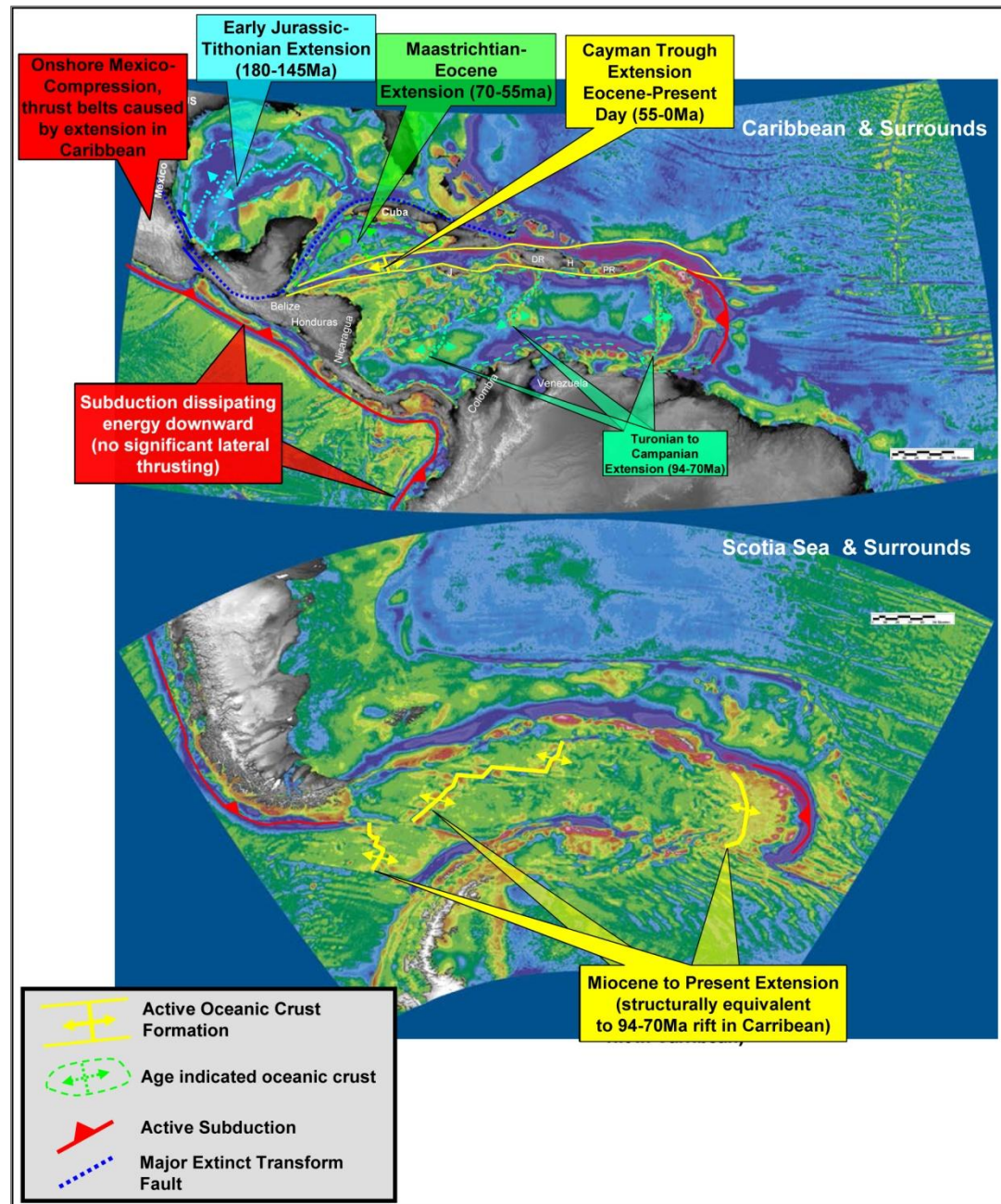


Figure 4. Present-day tectonic setting of the Caribbean (upper image) and Scotia Sea (lower image) expressed using gravity grids (CIRES, 2016). On the gravity image three Upper Cretaceous spreading ridges may be interpreted in the southern Caribbean Basin, just like within the Scotia Sea area.

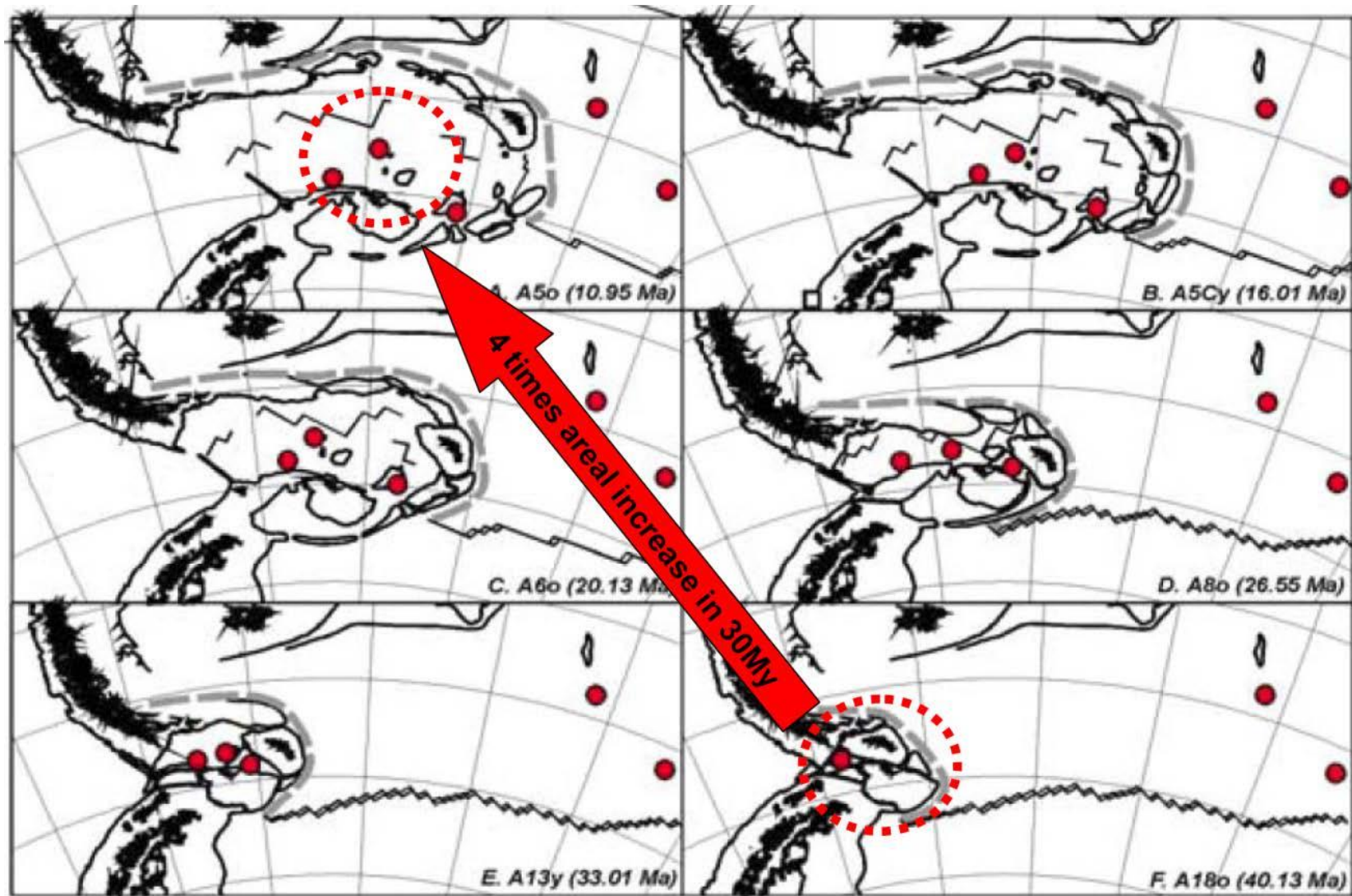


Figure 5. Scotia Sea in-situ plate model (after Barker, 2001).



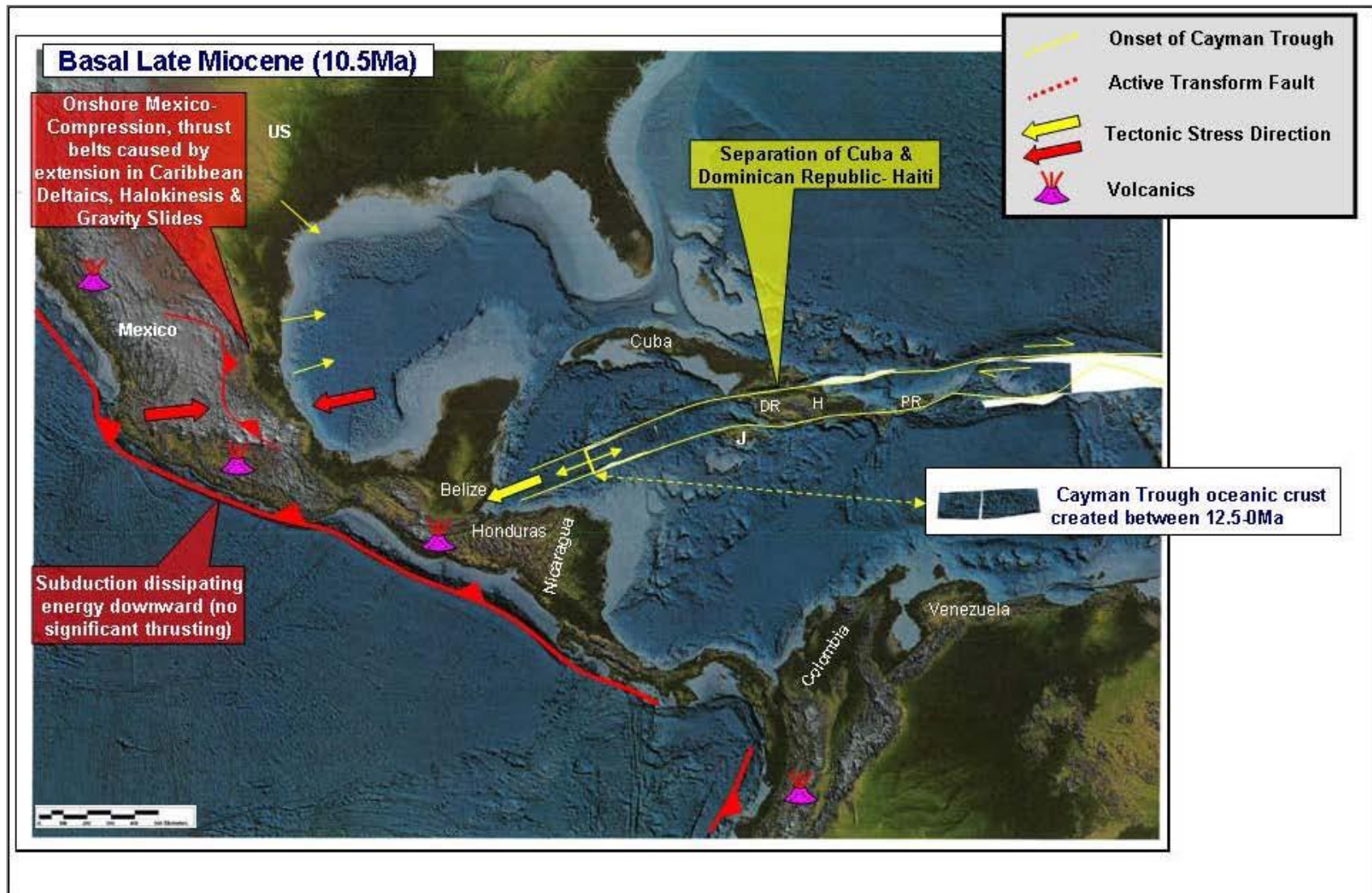


Figure 6. 10.5Ma earliest late Miocene Plate Reconstruction.

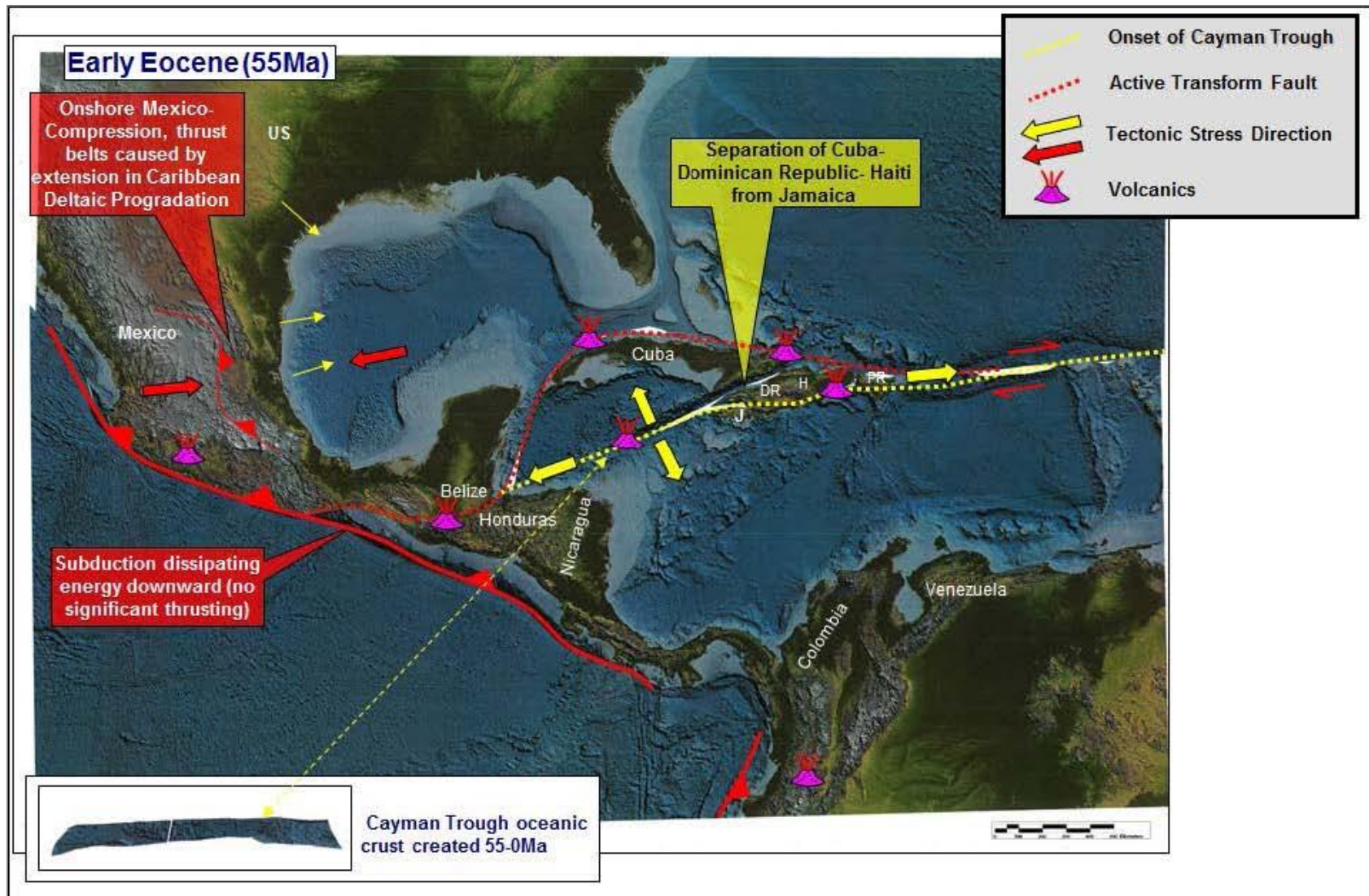


Figure 7. 55Ma early Eocene Plate Reconstruction at the onset of the Cayman Trough formation.



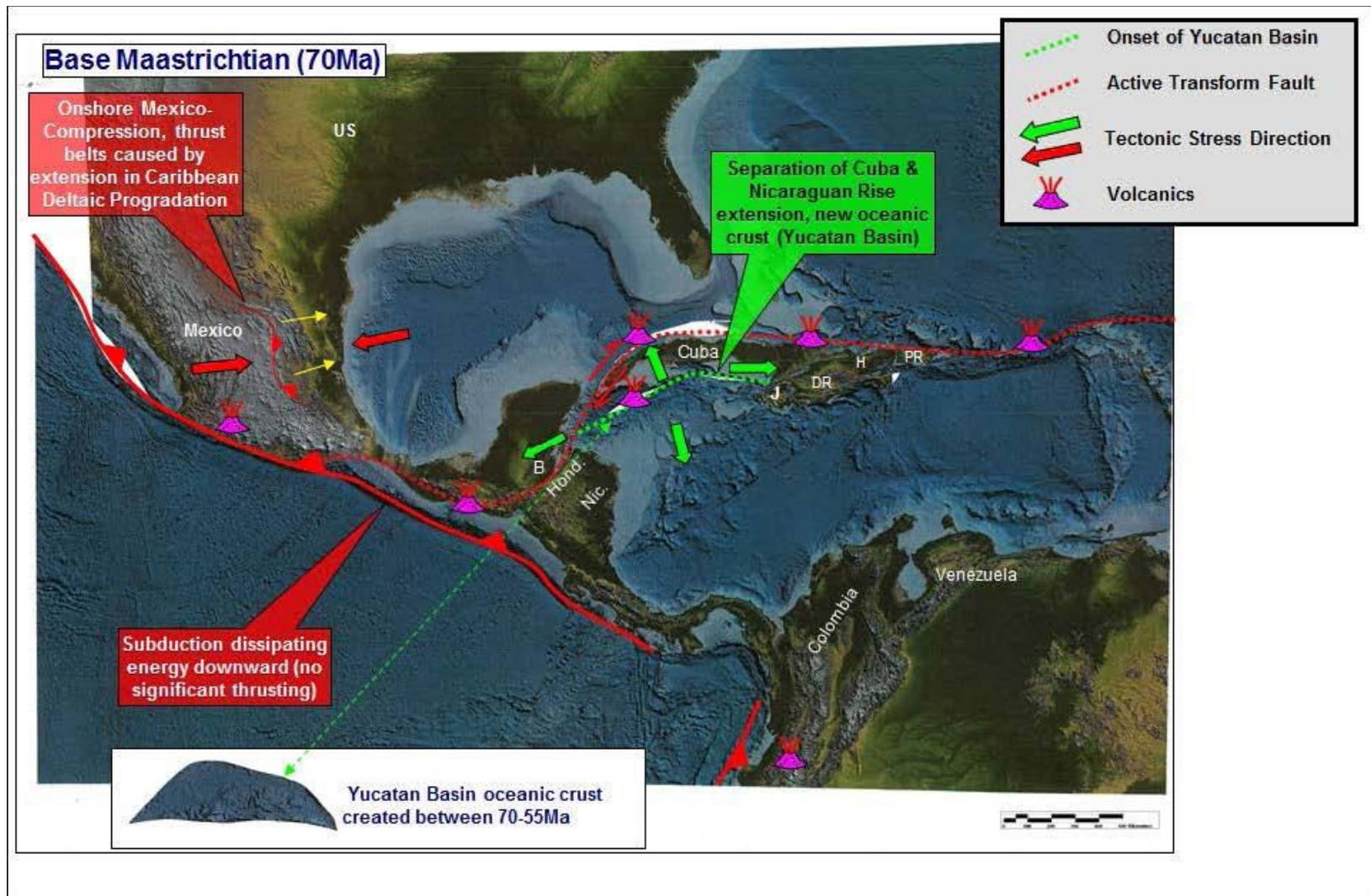


Figure 8. Maastrichtian plate reconstruction illustrating Cuba attached to Yucatan Platform east and Nicaraguan Rise to the south.



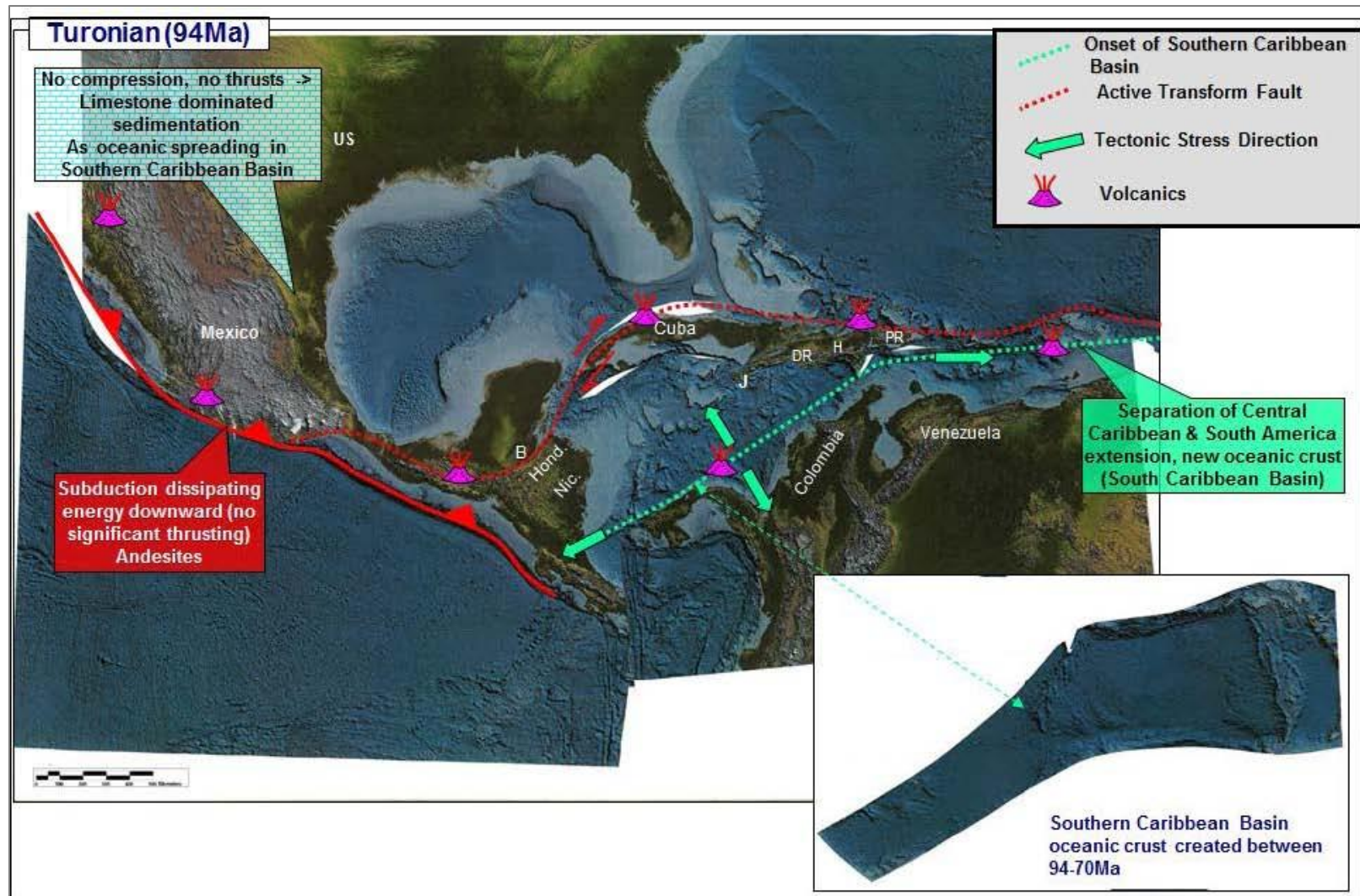


Figure 9. Turonian plate reconstruction illustrating connection of the Nicaraguan Rise, Jamaica, Hispaniola and Puerto Rico with South America.

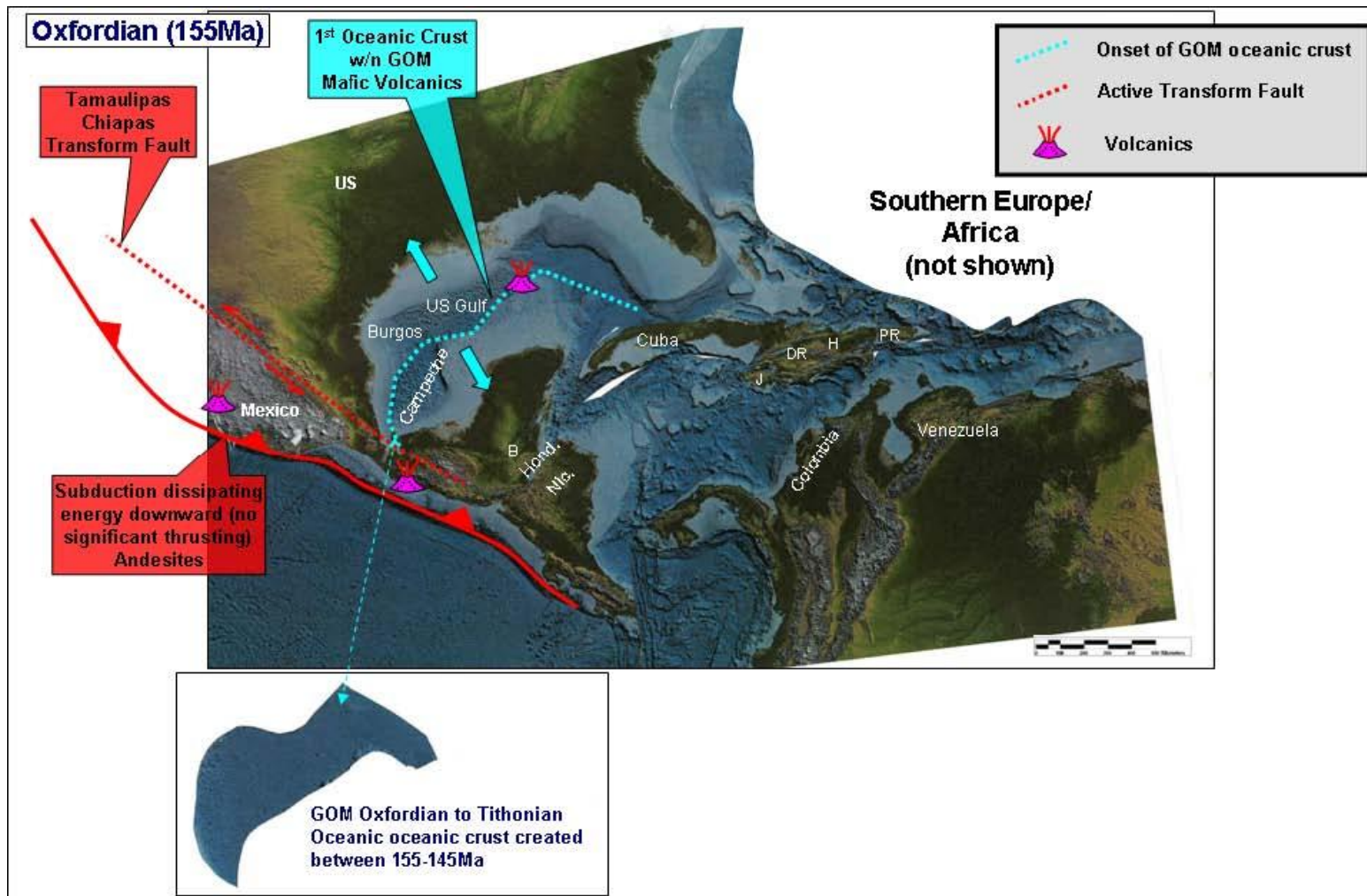


Figure 10. Oxfordian plate reconstruction illustrating location of GOM oceanic crust and spreading direction.



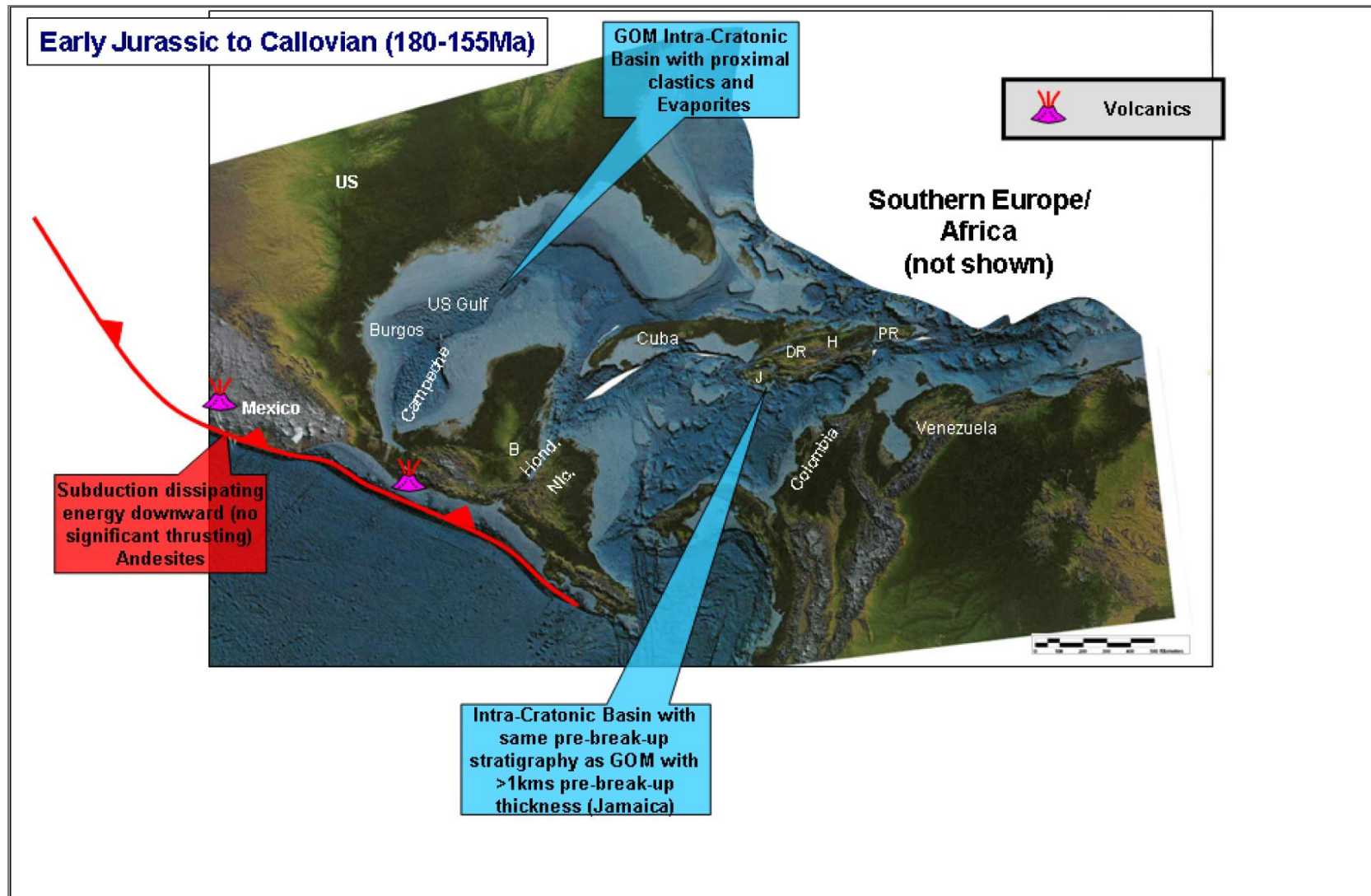


Figure 11. Early Jurassic to Callovian plate reconstruction illustrating pre-GOM oceanic crust microplate arrangement.

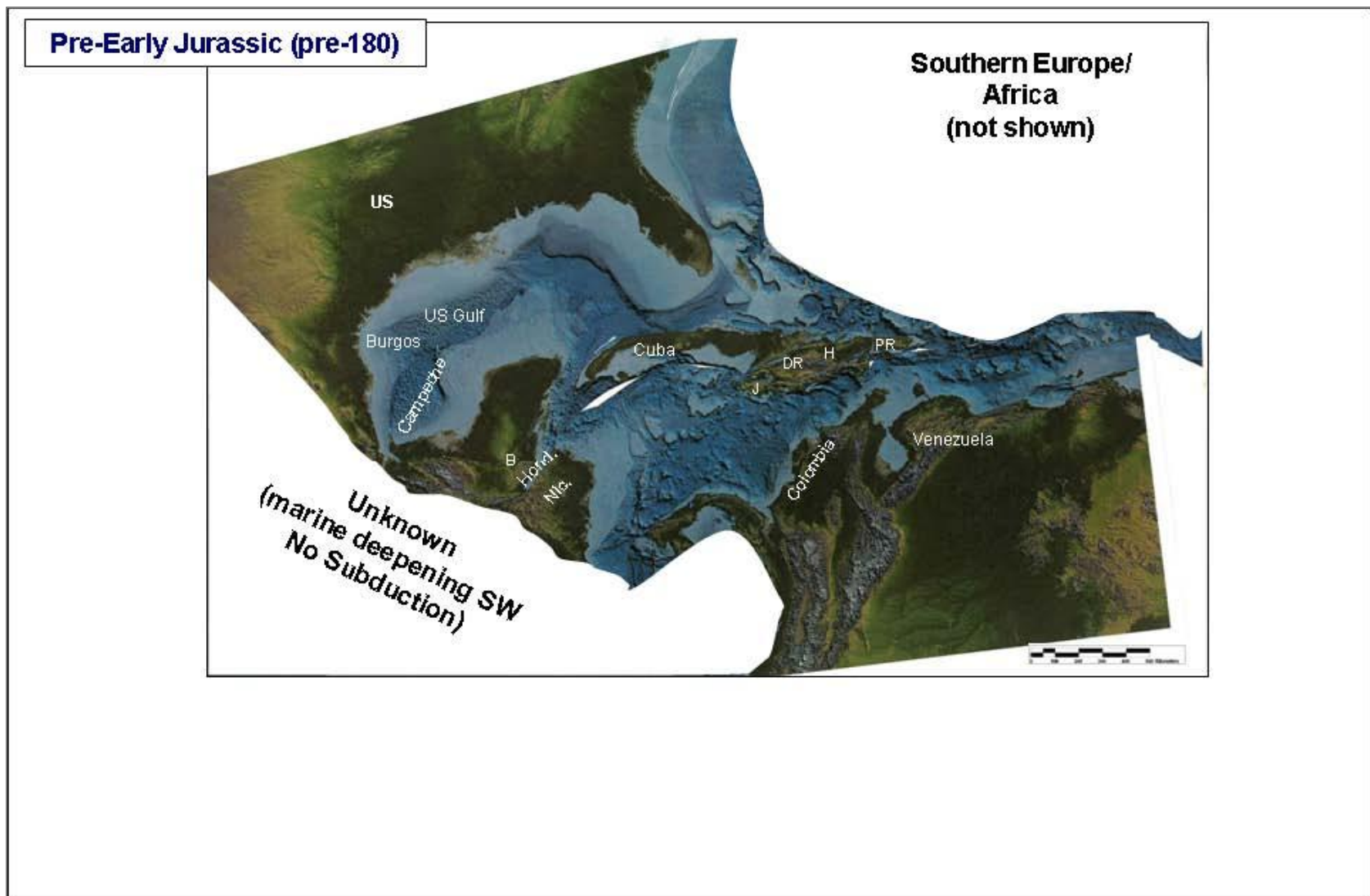


Figure 12. Permo-Triassic plate reconstruction illustrating initial location of present-day elements.