

Unthinkable Physical Analogs for the Modern Concepts on Continental Stretching and Rupturing*

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Search and Discovery Article #41128 (2013)

Posted June 17, 2013

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013, AAPG©2013

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Abstract

In the last five years geoscientists became familiar with very deep seismic sections at continental margins that display the complete structure of the crust and image further deep into the mantle. By interpreting these recent data obtained mostly in passive margins it was possible to recognize some tectonic features in the continental crust like the Moho (compositional) and Conrad (rheological) discontinuities, and, an overall tapering profile going from the original crust, through stretched, then thinned, and, finally, into hyper-extended crust ([Figure 1](#)). This taper profile may sometimes show irregularities due to necking of the crust adjacent to strong resistant continental ribbons or to mantle diapirs ([Figure 1](#) and [Figure 2](#)). A boudinage crustal profile is frequently observed. The continental-oceanic boundary (COB) may be represented by exhumed mantle in magma-poor margins ([Figure 3](#)) or by transitional crust and seaward-dipping reflectors (SDR's) in volcanic margins ([Figure 4](#)). All these structures have been reported in recent models dealing with new ideas on how mega continents rupture and break apart. Well sampled homologous continental margins such as Iberia-Newfoundland and intensively studied exhumed tethyan continental margins high in the Alps provided the basis for the development of such revolutionary new models (Manatschal, 2004; Manatschal et al., 2007; Péron-Pinvidic and Manatschal, 2009 and 2010). Recently, studies performed on the continental margins of the South Atlantic confirmed the main aspects outlined in these models (Unternehr et al., 2010; Zalán et al., 2011; Kumar et al., 2012).

As these studies progressed, geologists started to physically model the rupturing and breaking of materials possessing a rheological behavior close to the upper lithosphere; that is, the jelly sandwich model constituted by an upper brittle crust, a lower ductile crust, and an upper rigid mantle. Some of these physical models employed very common substances, easily found on our everyday routine and that would normally neither be considered for a scientific experiment nor be expected to replicate the deformation of rupturing mega continents. This work presents some of the modeling performed with such unthinkable physical analogs.

One of these non-conventional analogs is the everyday breakup of a chocolate bar ([Figure 5](#)). Starting with an initial undeformed bar ([Figure 5A](#)), the chocolate body is composed of an external brittle crust and an internal creamy filling that plays the role of the lower ductile crust. In this initial stage, the chocolate bar replicates a stable mega-continent. As stretching starts, initial cracks can immediately be noticed, perpendicular to the stretching direction. It is the beginning of the rift phase ([Figure 5B](#)). As stretching/rifting continues a conspicuous necking

develops in a certain point, indicating a region that is more prone to stretching. This represents an H-Block ([Figure 5C](#)). From now on most of the stretching of the chocolate bar will take place along this H-Block which will rapidly go into hyper-extension ([Figure 5D](#)). Just before breakup, the chocolate bar is almost separated but there is still a narrow bridge of ductile material linking the almost split apart pieces ([Figure 5E](#)). After breakup the chocolate bar is divided into two masses. The one in the left remained with the hyper-extended portion of the H-Block and was blessed (in terms of petroleum richness) with a wide continental margin. The other mass to the right shows an abrupt tapering profile and an extremely narrow continental margin ([Figure 5F](#)). It is noteworthy to point out that the profiles shown by the chocolate bar in [Figure 5C](#), [Figure 5D](#), [Figure 5E](#), and [Figure 5F](#) are very similar to the tapering profiles found in real ultra-deep seismic sections ([Figure 1](#), [Figure 2](#), [Figure 3](#), [Figure 4](#), [Figure 5](#), and [Figure 6](#)).

But not all analogs are made up of such scientifically unexpected components. “Normal” rocks may display meso-scale deformations that closely resemble the deep structure of magma-poor passive margins. All these analogs will be compared with ultra-deep seismic lines shot on both sides of the South Atlantic Ocean.

Acknowledgements

I thank the management of ION-GX Technology for the permission to present the seismic line shown in [Figure 2](#).

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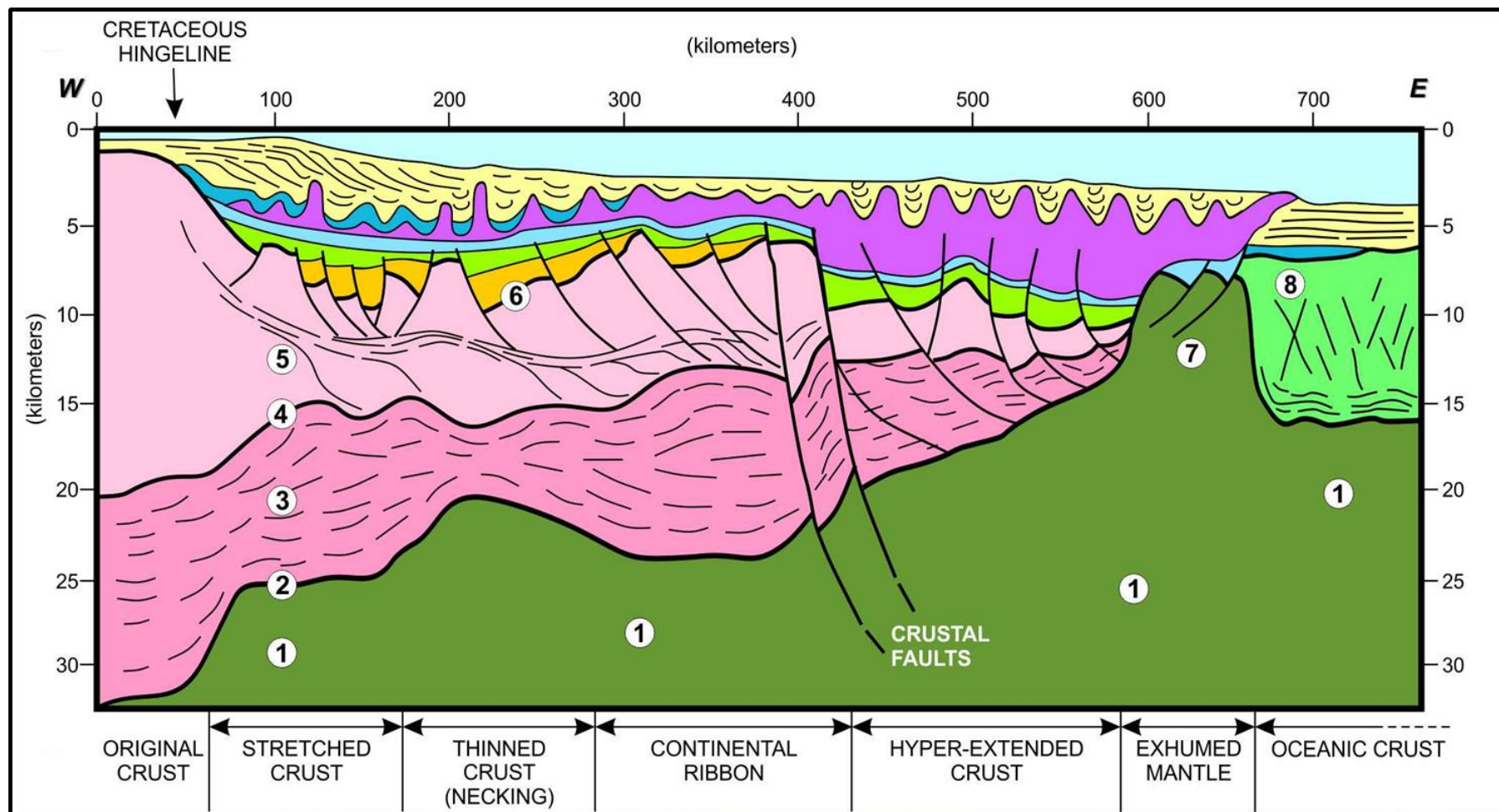


Figure 1. Schematic W-E geologic profile valid for the magma-poor Santos, Campos, and Espírito Santo Basins of Southeastern Brazil, displaying the common strain domains of the continental crust (in pink colors) and its contact with oceanic crust via an intervening exhumed mantle. Elements of the basement are numbered as (1) mantle, (2) Moho, (3) lower ductile crust, (4) Conrad, (5) upper brittle crust, (6) top of crystalline basement, (7) exhumed mantle, and (8) oceanic crust. Sedimentary packages above (6) represent early syn-rift (dark yellow), late syn-rift (green), early sag (light blue), aptian evaporates (purple), albian carbonates (dark blue), Cenomanian-Recent siliciclastics (light yellow). Based on several works presented by Petrobras in several meetings and symposia (for instance, Zalán et al., 2009; Zalán et al., 2011) and on [Figure 2](#) (below). The important characteristic to be noticed here is the tapering profile of the continental crust, typical of a material that had been pulled laterally and strained to great extent in a mixed brittle-ductile manner until its thinned extremity parted away from the other portion of continental crust.

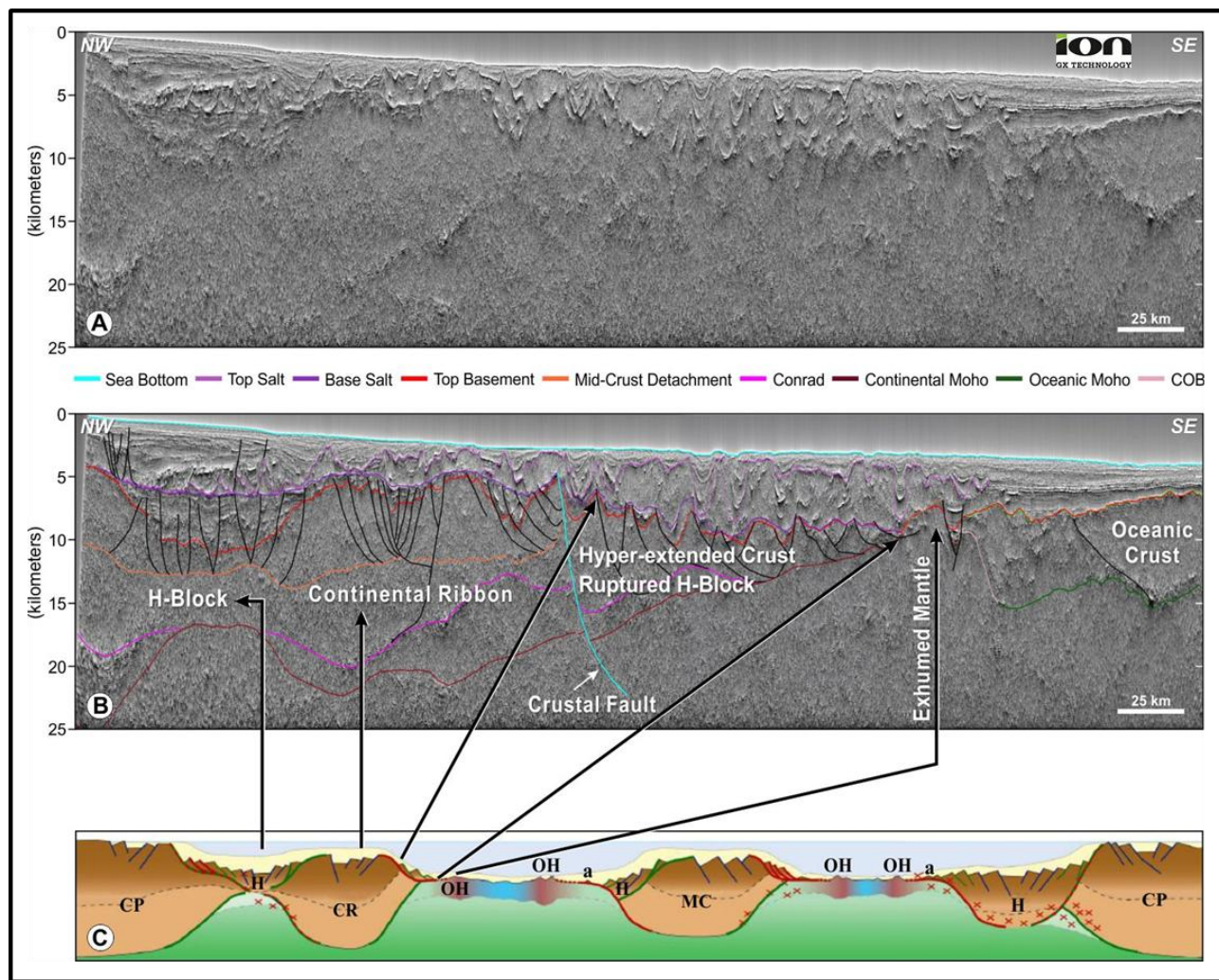


Figure 2. Two-dimensional ultra-deep depth seismic section shot in dip direction in the Santos Basin (acquired by and shown under permission from ION-GXT). Comparison of an interpreted seismic section with the types of continental crustal blocks presented in Péron-Pinvidic and Manatschal (2010). A – Non-interpreted. B – Interpreted (see color-code between seismic lines)(interpretation of seismic line done in conjunction with Maria do Carmo G. Severino from Petrobras). C – Lower part of their Figure 4 inverted in order to allow a better comparison with our Figure 2B. The similarity is amazing. From left to right the seismic section presents a failed H-Block, a continental ribbon, a ruptured H-Block (hyper-extended crust, much wider than in the model example), the outer high constituted by the exhumed mantle, and the oceanic crust. Visualization of seismic section in tecVA_RFASE (Petrobras patented in-house technique). The tapering profile of the continental crust is overwhelming. Notice that under the failed H-Block a mantle diapir perforated and separated the ductile lower crust.

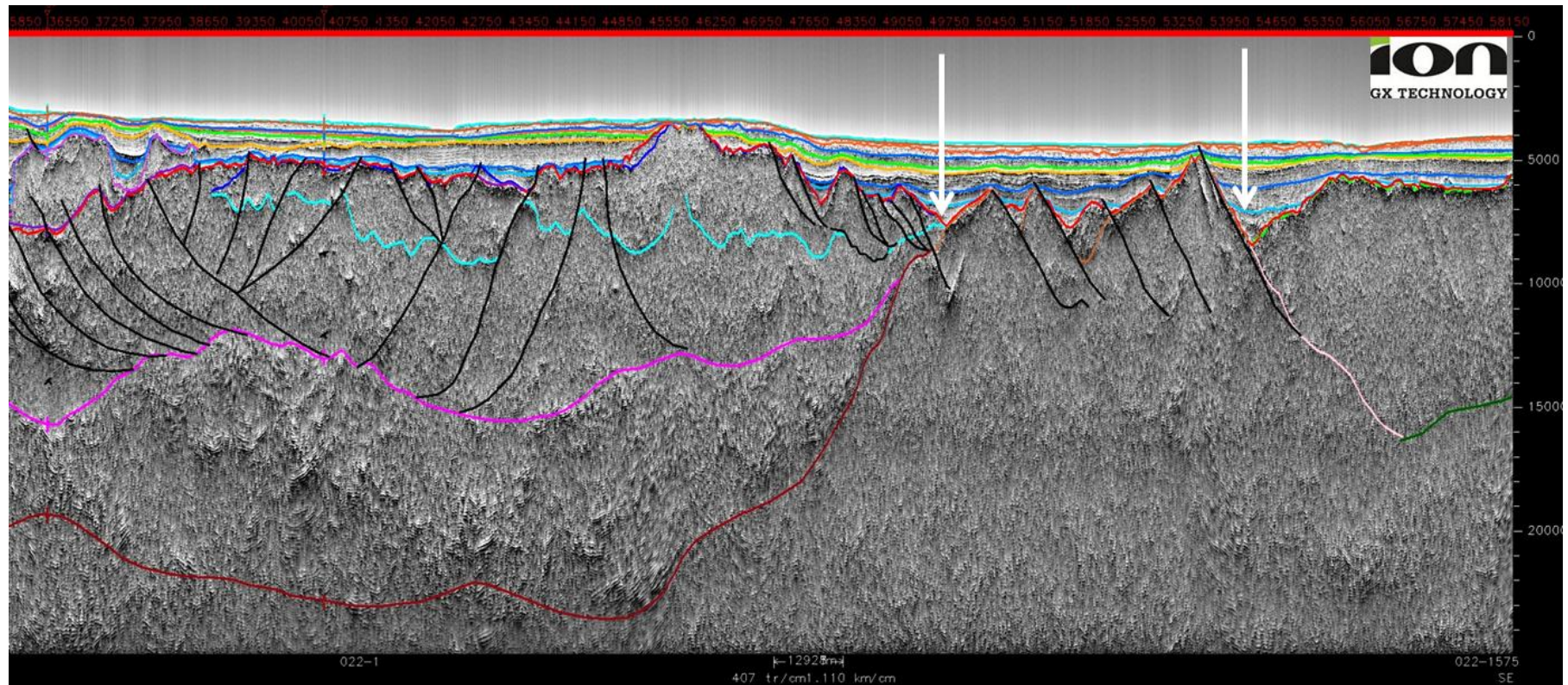


Figure 3. Two-dimensional ultra-deep depth seismic section shot (by ION-GXT) in dip direction in the Santos Basin (from Zalán et al., 2011) displaying the dual nature of the continental crust (upper brittle and lower ductile crusts), the exhumation of the mantle (between arrows), and the passage to oceanic crust. Also shown are the Conrad and Moho discontinuities. Notice that exhumed mantle underwent extension by planar rotational faults at shallow levels, indicating that rifting was still taking place during exhumation. Visualization of seismic section in tecVA_RFASE (Petrobras patented in-house technique). Although the continental crust is thick and resembles a resistant continental ribbon its termination also shows a very abrupt thinning/tapering profile, to the left of exhumed mantle, suggesting a last stretching strain before final rupture.

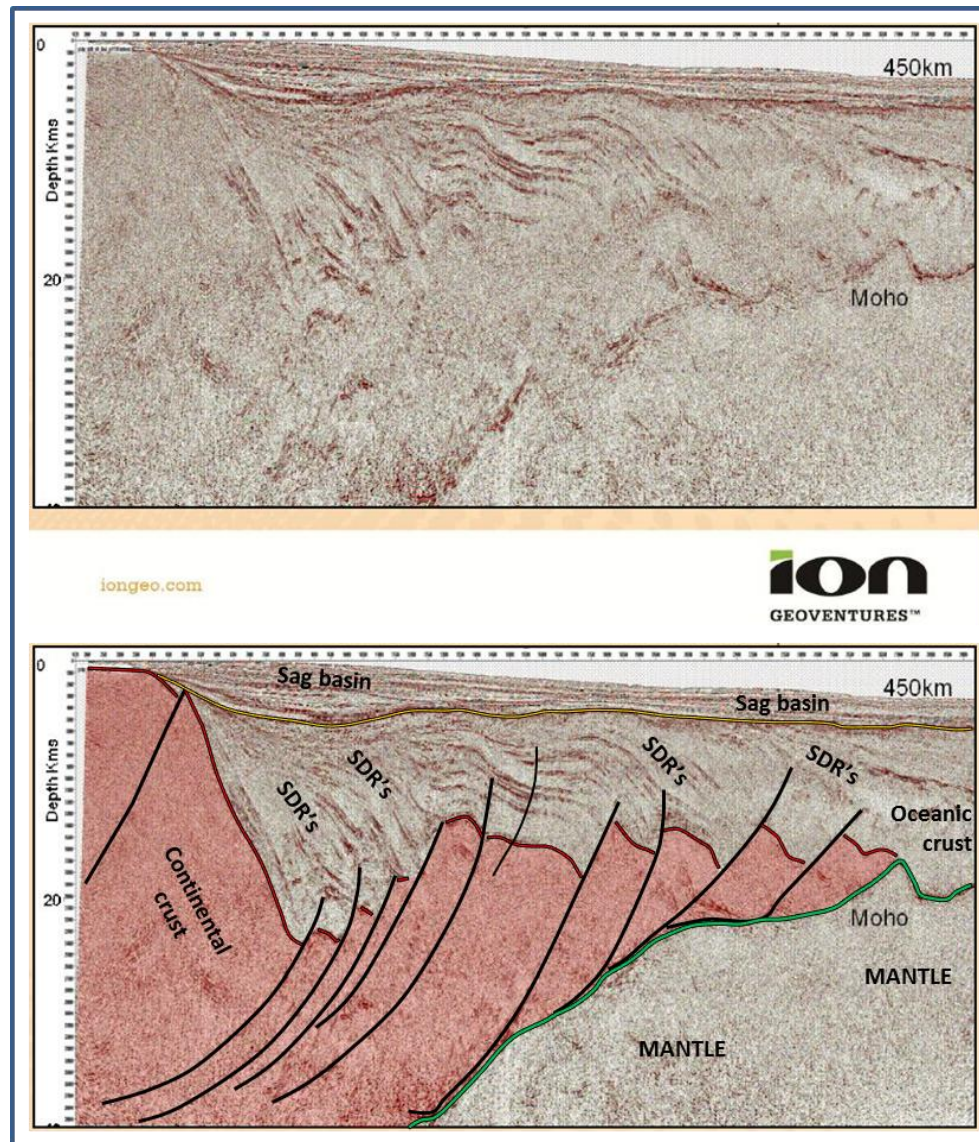


Figure 4. Seismic section taken from ION-GXT advertisement folder for PELOTAS SPAN. Non-interpreted and interpreted versions. Notice the typical geology of a volcanic passive margin, where the rifts are fully filled by volcanic material (Seaward Dipping Reflectors, SDR's). Even in this type of basin the continental crust presents the hyper-extended profile of a material that had been stretched in a mixed brittle-ductile mode and strained like a dry bubble gum before final rupture. There was no exhumation of mantle by the time of breakup because it was completely covered by SDR's; although a small diapir of mantle can be seen at the continental-oceanic crust boundary.

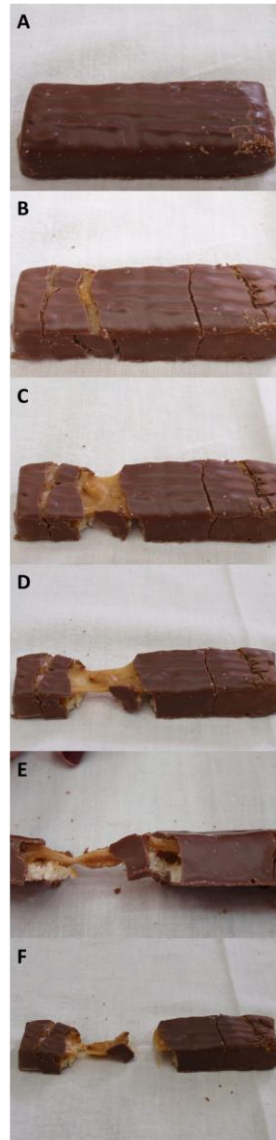


Figure 5. Experimental stretching and rupturing of a chocolate bar, composed of an external brittle crust and a creamy ductile filling playing the role of lower crust. The analogy with the stretching and breakup of a continental mass is amazing. A – Underformed continental mass. B – Initial breaking of the crust, rift phase. C – Continuation of rifting and development of necking (H-Block). D – Hyper-extension along H-Block. E – Seconds before final breakup the continental crust is still attached via a narrow ductile bridge. F – Rupture took place with the development of a wide continental margin (to the left) and a narrow continental margin (to the right).

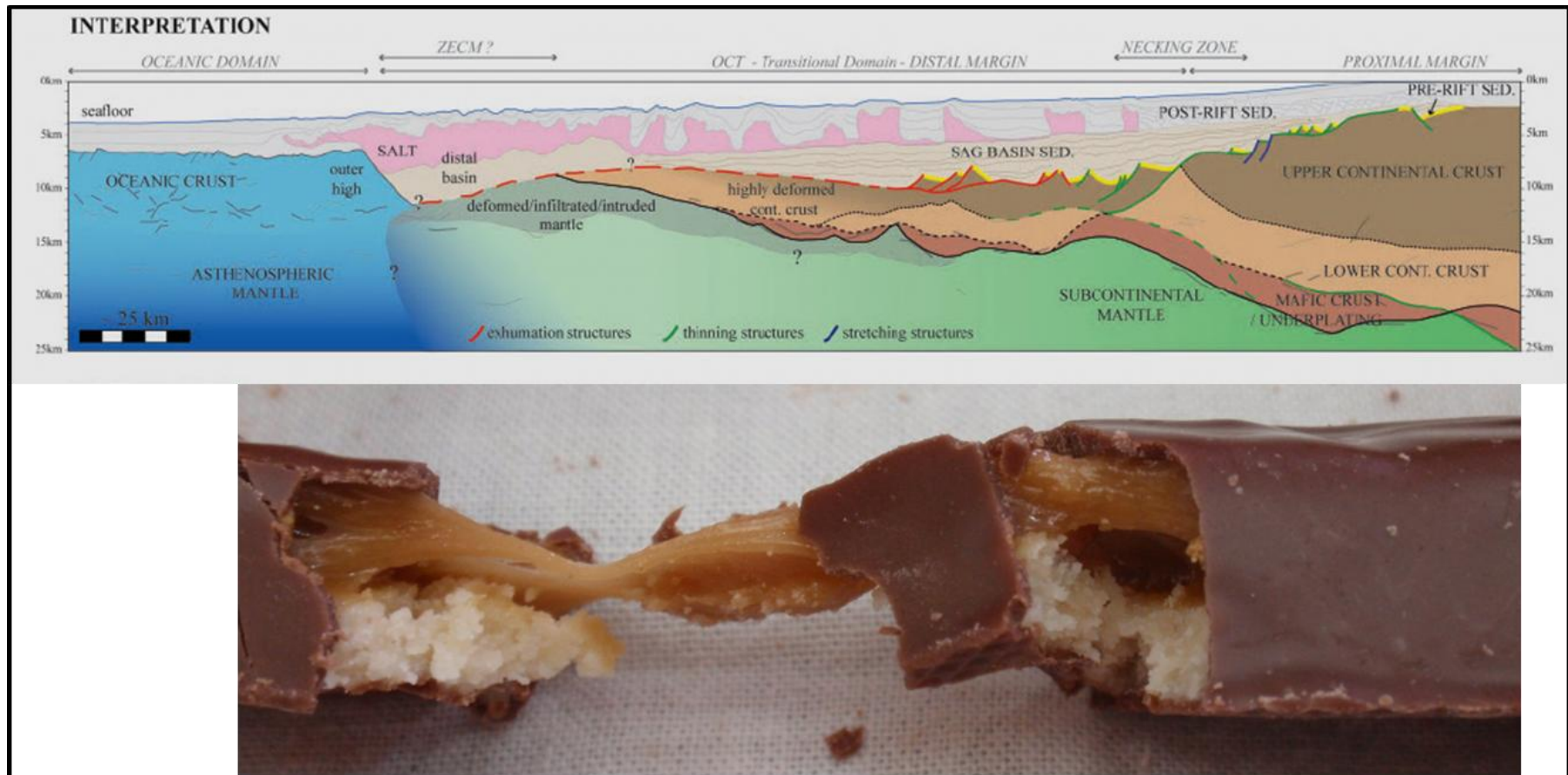


Figure 6. Comparison of a stretched and thinned continental margin in Angola (from Unternehr et al., 2010) with [Figure 5E](#). The resemblance is fantastic and it suggests that the rupture, thinning, and breakup of a mega-continent follows the same simple principles of the stretching of a chocolate bar.