# FORMATION OF THE COLORADO HIGH OFFSHORE ARGENTINA

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## RESUMEN

El Alto de Colorado es un gran alto de basamento costa afuera en Argentina, situado en la intersección entre la Cuenca de Colorado al oeste y la Cuenca Argentina al este. Esta situación geográfica da lugar a una combinación de sobreimposiciones tectónicas que confieren características únicas al Alto de Colorado, tanto en su evolución estructural como en su potencial de exploración.

Durante la fase principal de rifting que formó la Cuenca de Colorado, el adyacente Alto de Colorado estuvo sujeto a una menor formación de fallas, las cuales fueron más localizadas. Al mismo tiempo que se producía una rápida subsidencia en la Cuenca de Colorado, una inclinación regional hacia el oeste marcaba las fases iniciales en la formación del Alto de Colorado.

Un intenso magmatismo en la adyacente Cuenca de Orange, en el margen africano, se propagó hacia el oeste, causando la formación de una serie de "seaward dipping reflectors" (SDR) al este de la Cuenca de Colorado. Durante la subsiguiente ruptura continental, las partes exteriores del margen argentino se vieron sujetas a un levantamiento estructural y a una profunda erosión. A continuación se produjo un hundimiento térmico del recientemente formado margen pasivo atlántico, una inclinación de la Cuenca Argentina hacia el este y la formación del flanco este del Alto de Colorado. La formación adicional de fallas post-ruptura contribuyó significativamente a la estructuración del alto. Finalmente, la subsidencia continua durante el Cretácico Superior tanto en la Cuenca de Colorado como en la Cuenca Argentina condujo al desarrollo de un mega-cierre estructural en el Alto de Colorado.

Conteniendo varios "plays" prometedores y la posibilidad de migración de hidrocarburos desde rocas generadoras maduras tanto al oeste como al este, las licencias operadas por Equinor en el Alto de Colorado contienen un sustancial potencial exploratorio.

## INTRODUCTION

The Colorado High is a regional structural high located in the outboard part of the Atlantic continental margin of Argentina, more than 300 km from the coast (Fig. 1). It is a basement high with significant exploration potential located at the intersection between the Colorado Basin to the west and the Argentine Slope Basin to the east. The interplay between the tectono-magmatic evolution of these two basins led to formation of very large 4-way closures mapped at several

stratigraphic levels (Wathne *et al.* 2022). With mature source rocks of Barremian to Early Albian age predicted in both the Colorado Basin and the Argentine Slope Basin, the mega-closure on the Colorado High could have acted as regional focus for migration of significant volumes of hydrocarbons from both basins.

Two licences are located on the Colorado High. Equinor is the operator of both licences, with YPF and Shell as partners in the CAN_100 licence. A planned exploration well on the Argerich prospect in the CAN_100 licence will be drilled within the mega-closure described above. The adjacent CAN_108 licence where Equinor holds 100% equity also includes prospects within the mapped mega-closure.

The exploration potential of the Colorado High is genetically linked to the key geological events that controlled its formation history. Hence, a regional scale analysis of these events has been performed and is described below.

## DATABASE

For the regional interpretation 2D seismic data from different vintages were used, which are of varying quality. Modern, high quality 2D seismic data acquired by ION and Spectrum/TGS were adding important information and allowed an interpretation of the regional fault pattern, however, with a line spacing of 10-20 km the seismic coverage is rather low, but sufficient to get a good understanding of the tectonic evolution of the Colorado Basin and the Argentine passive

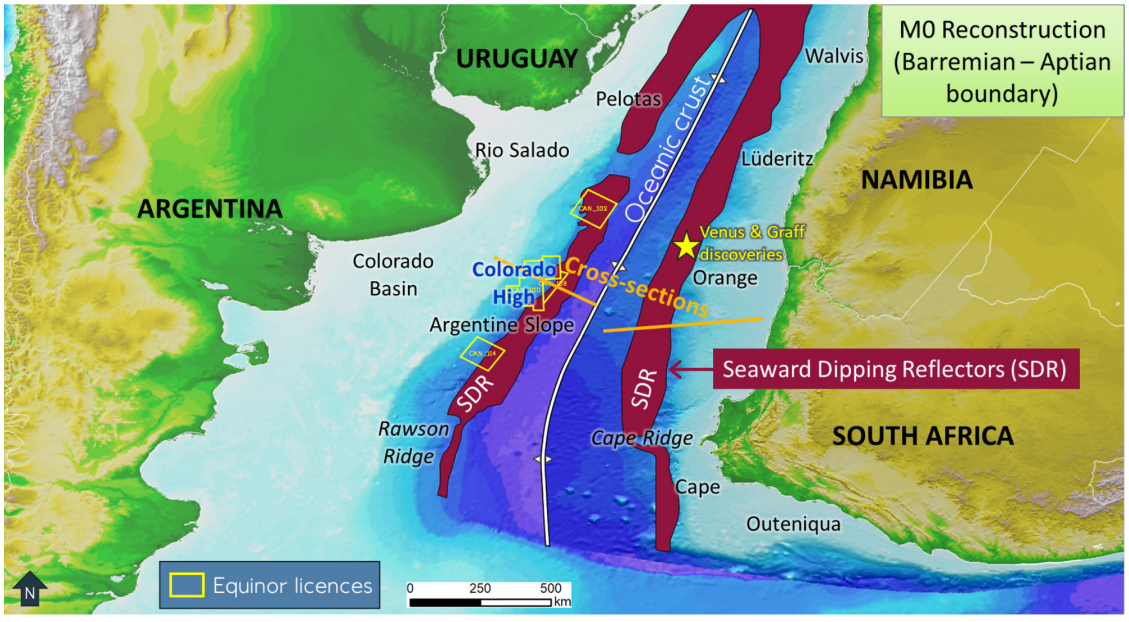


**Figure 1. Locations of conjugate margin cross-sections on a plate tectonic reconstruction of the Southern South Atlantic. The reconstruction is calibrated in time to the formation of the M0 magnetic anomaly, approximately corresponding to the Barremian – Aptian boundary.**

margin. In CAN_100 3D seismic data acquired in 2007 and reprocessed in 2021 were available, which provided a much better imaging of the complex fault pattern and pre-breakup stratigraphy. Compilations of gravity and magnetic data from different surveys were integrated into the regional study.

## REGIONAL TECTONIC FRAMEWORK

The Colorado High is positioned in the outer part of continental margin of Argentina, with transitional crust represented by seaward dipping reflectors (SDR) mapped on seismic to the east (Fig. 2). Formation of such SDR units is commonly ascribed to the final stage of magmatism ultimately leading to continental breakup (Hinz *et al.* 1999). Thus, correlations to the conjugate margin of Africa and evaluations of key processes related to the opening of the southern South Atlantic Ocean have been incorporated in the analysis of the Colorado High.

The outer part of the Argentinian continental margin is narrow and steep, often lacking evidence of major rifting prior to the formation of the SDR wedges. In contrast, the African conjugate margin is wide, commonly associated with thick magmatic dominated syn-rift units (Fig. 2). Hence, in our regional tectono-magmatic model we infer asymmetric rifting with most of the lithospheric thinning, magmatism and syn-rift deposition occurring on the African side.

The Colorado Basin is interpreted as a continental rift basin, only indirectly affected by the opening of the southern South Atlantic Ocean to the east. Many syn-rift wedges have been mapped on seismic data, but very few of these have been penetrated by wells. Furthermore, the syn-rift sediments encountered in wells have been interpreted to be deposited in a continental setting. Hence, they provide little data to constrain the stratigraphic ages of these units and timing of onset of rifting responsible for the formation of the Colorado Basin.

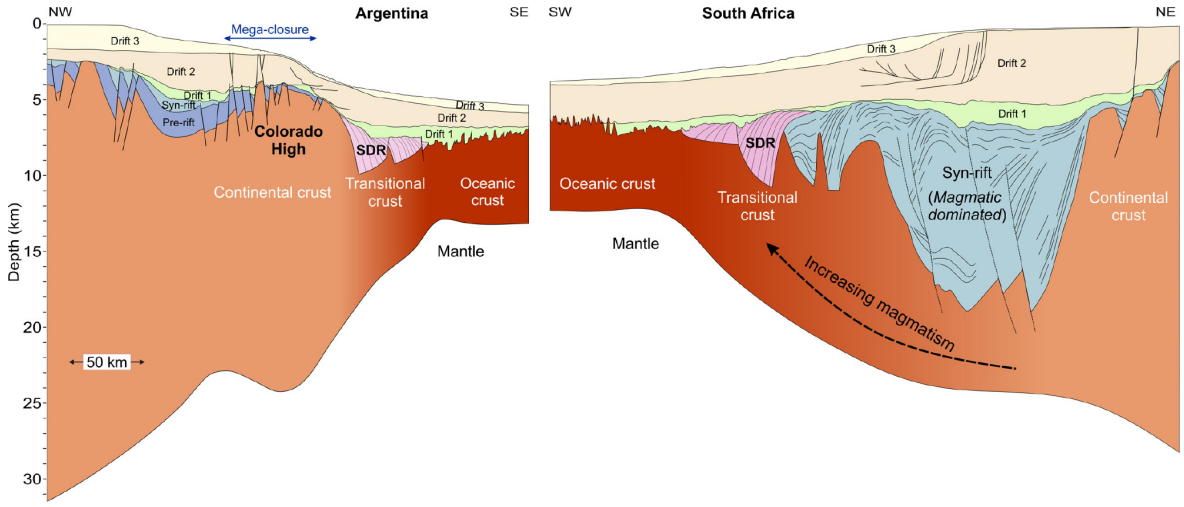


**Figure 2. Argentina - South Africa conjugate margin cross-sections. Locations of the cross-sections are displayed on the map in Figure 1.**

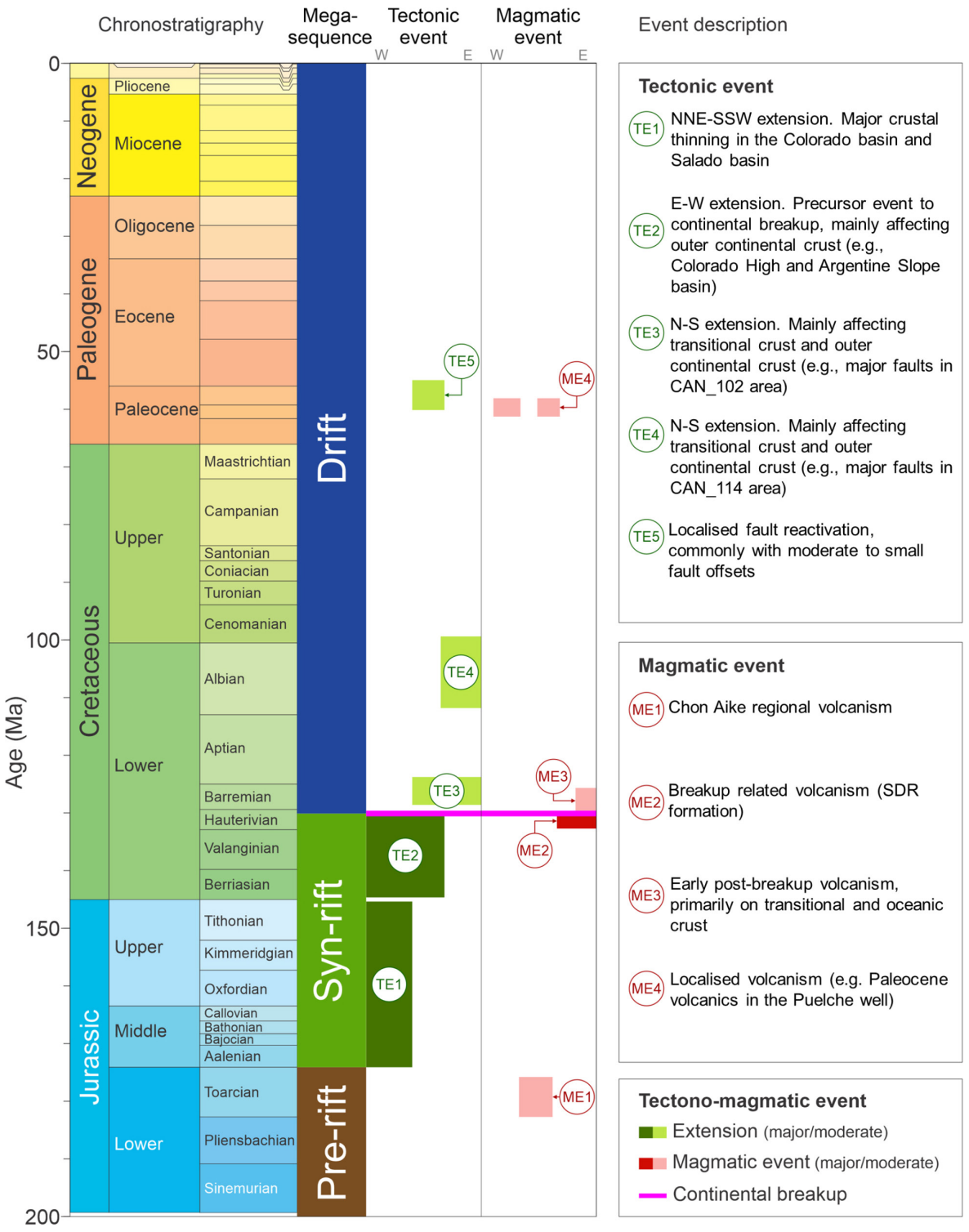


Figure 3. Tectono-magmatic event chart for the Atlantic margin of Argentina.

Based on integrated interpretations of our comprehensive database of wells, seismic, gravity and magnetic data, we have built a regional tectono-magmatic framework with five tectonic events and four magmatic events (Fig. 3). This framework has enhanced our geological models for the margin evolution and the formation of the Colorado High.

Faults displayed on the basement depth map in figure 4 are colour coded according to the tectonic phases in which the faults were most active. TE1 faults are common in the Colorado Basin, causing significant crustal thinning and the establishment of the Colorado Basin as a major continental rift basin. We interpret these faults to be generated by a phase of NNE-SSW extension. A marked change in the regional stress field is inferred towards the end of Jurassic. This marks the onset of the TE2 event with dominant E-W extension (Fig. 3). The faults with main activity during the TE2 event are concentrated in the outer parts of the Argentinian margin, with some reactivation of older structures further inboard.

At the same time as the crustal thinning of the TE2 event became more and more focused on the outermost part of the Argentinian margin, intense volcanism during the ME2 magmatic event formed symmetric sets of SDR wedges on both southern South Atlantic margins (Fig. 2). This finally led to continental breakup and the birth of the South Atlantic Ocean.

During the continental breakup process both margins were subjected to regional uplift and deep erosion. Consequently, a regional angular unconformity was formed on both margins. This unconformity, commonly referred to as the "Breakup unconformity" has on both margins been tied to the top of the SDR wedges and traced a long distance inboard.

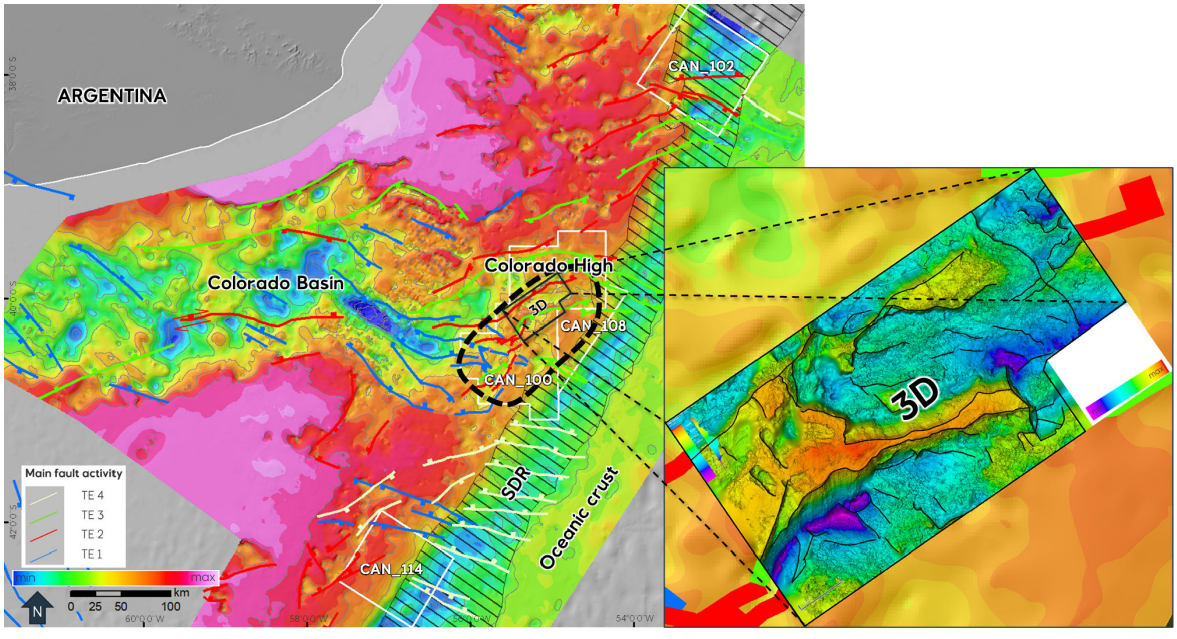


Figure 4. Left: Regional Top Basement interpretation in depth with regional fault interpretation based on 2D seismic data. The faults are coloured according to the age of main fault activity (Fig.3). The location of the Colorado High is marked as a black dashed polygon. Right: 3D seismic interpretation of basement in time with main fault trends as black lines.

Significant post-breakup faulting occurs along the Argentinian continental margin. By regional seismic correlations two distinct post-breakup tectonic phases (TE3 & TE4) have been identified. N-S extension has been inferred for both the TE3 and TE4 events. TE3 faults have been mapped in the Colorado Basin, on the Colorado High and in the vicinity of the CAN_102 licence in the north (Fig. 4). The younger TE4 faults are concentrated south of the Colorado High.

## STRUCTURAL EVOLUTION OF THE COLORADO HIGH

We interpret the Colorado Basin to be initially formed by significant crustal thinning during the TE1 tectonic event (Fig. 3). During this early rifting stage, the Colorado High was subjected to less and more localised faulting than the main part of the Colorado Basin. The western part of the area that makes up the present-day Colorado High was slightly rotated down towards the west. Hence, at this early stage the Colorado High was probably not yet established as a major structural high, and the western part was effectively representing the distal easternmost flank of the rapidly subsiding Colorado Basin to the west.

Active faulting occurred on the Colorado High during the subsequent TE2 tectonic event. At same time intense magmatism occurred in the adjacent Orange Basin to the east. As this magmatism propagated westward, breakup related SDR wedges were formed immediately to the east of the Colorado High. The elevated thermal regime during the ME2 magmatic event and the subsequent continental breakup led to major uplift and deep erosion on the Colorado High.

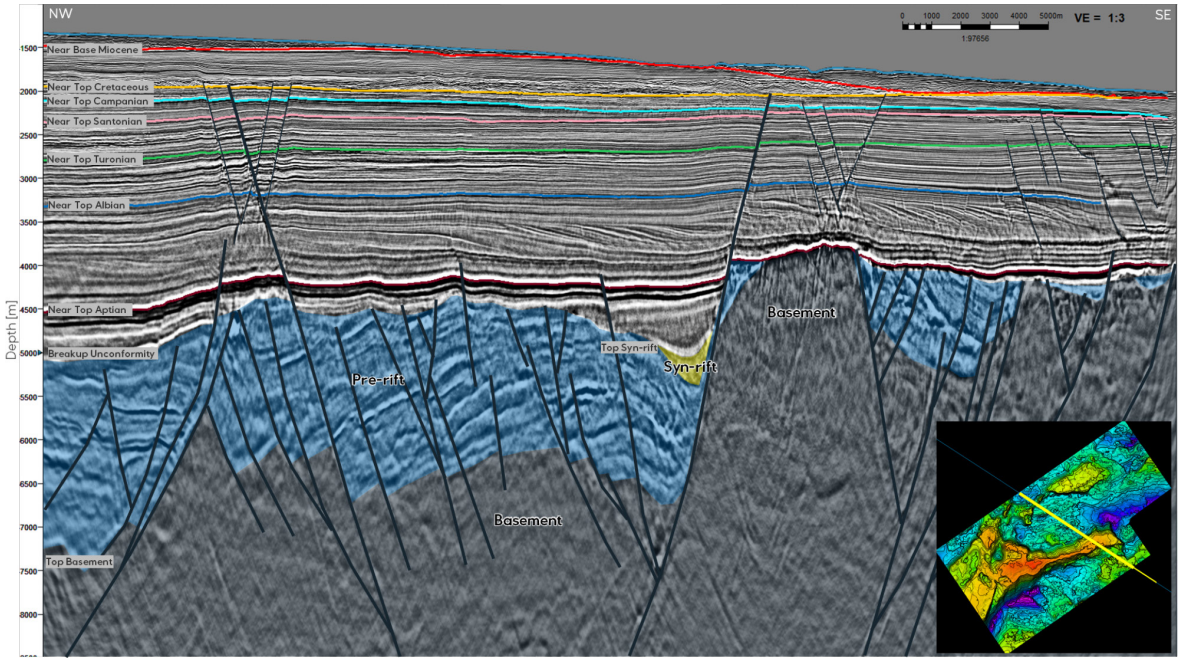


**Figure 5. 3D seismic depth section along the regional cross-section with seismic interpretation showing the complex fault pattern generated during several tectonic phases.**

Shortly after breakup regional thermal subsidence of the newly formed Atlantic passive margin caused rotation down to the east and formation of the east dipping flank of the Colorado High. Hence, we infer that the Colorado High as prominent structural high was established at this time. During the same period the Colorado High was also subjected to post-breakup extensional faulting of the TE3 tectonic event. Some of these faults were moderately reactivated later in Cretaceous (Fig. 5).

Major subsidence occurred in Late Cretaceous both in the Colorado Basin and the Argentine Slope Basin. This caused gradual accentuation of the structural relief of the Colorado High and led to development of a mega-closure within the CAN_100 and CAN_108 licences (Fig. 6).

The remarkably large post breakup subsidence observed in the Colorado Basin is an important factor for the formation of the mega-closure on the Colorado Basin. Yet, the size of the extensional faults and the thicknesses of the syn-rift sediments in the basin are rather small in comparison. However, an intriguing magnetic anomaly has been mapped in the eastern part of the Colorado Basin. Modelling of gravity and magnetic data indicate that a very large magmatic body with high densities might be located below the syncline mapped on seismic in this area (Fig. 7). Such a high-density body might have made significant contributions to the basinward rotation of the western flank of the Colorado High and thereby increasing the size of the mapped mega-closure.

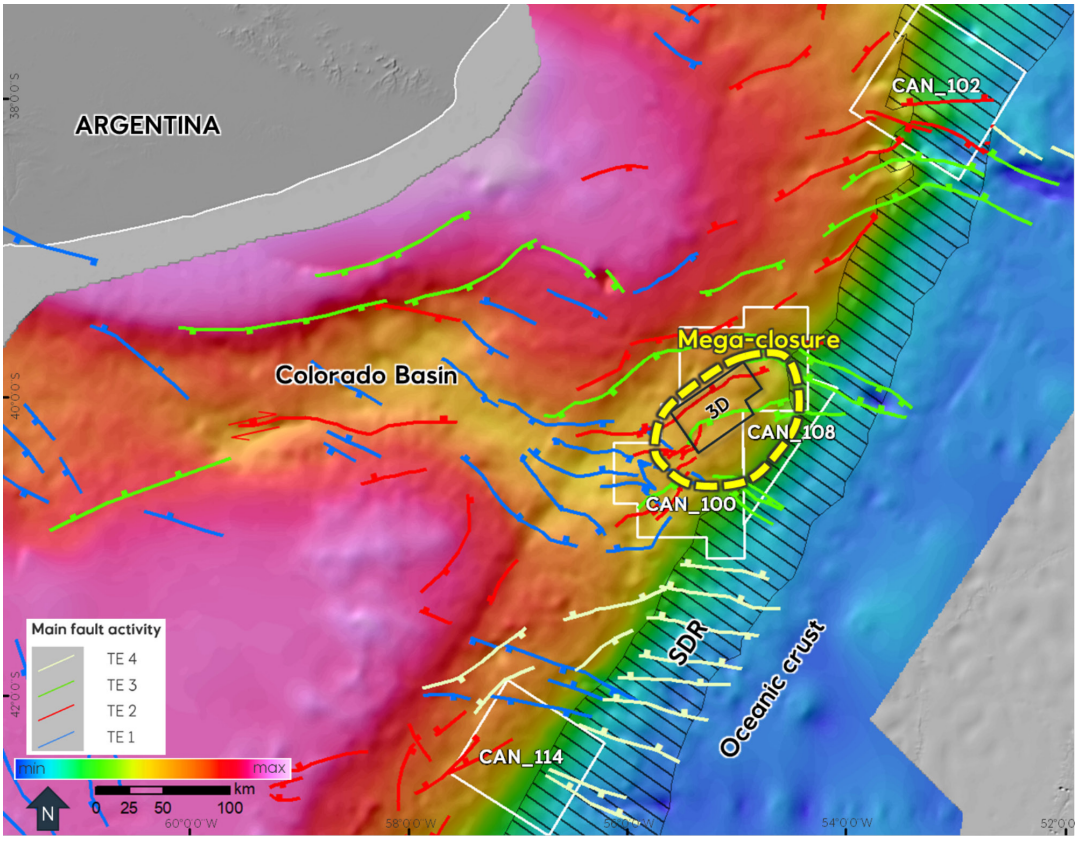


**Figure 6. Regional Breakup unconformity interpretation in time with regional fault interpretation based on 2D seismic data. The faults are coloured according to the age of main fault activity (Fig.3). The location of the Colorado High mega-closure is marked as a yellow dashed polygon.**

## IMPLICATIONS FOR PETROLEUM EXPLORATION

The formation history for the Colorado High makes it unique in the southern South Atlantic region. The high is very large, includes a mega-closure and is optimally located to act as a regional focus for petroleum migration from independent oil generating kitchens in the Colorado Basin to the west and the Argentine Slope Basin to the east (Hinsken *et al.* 2022). Several viable plays have been mapped on the Colorado High and will be tested by the Argerich-1 well in the CAN_100 licence (Wathne *et al.* 2022).

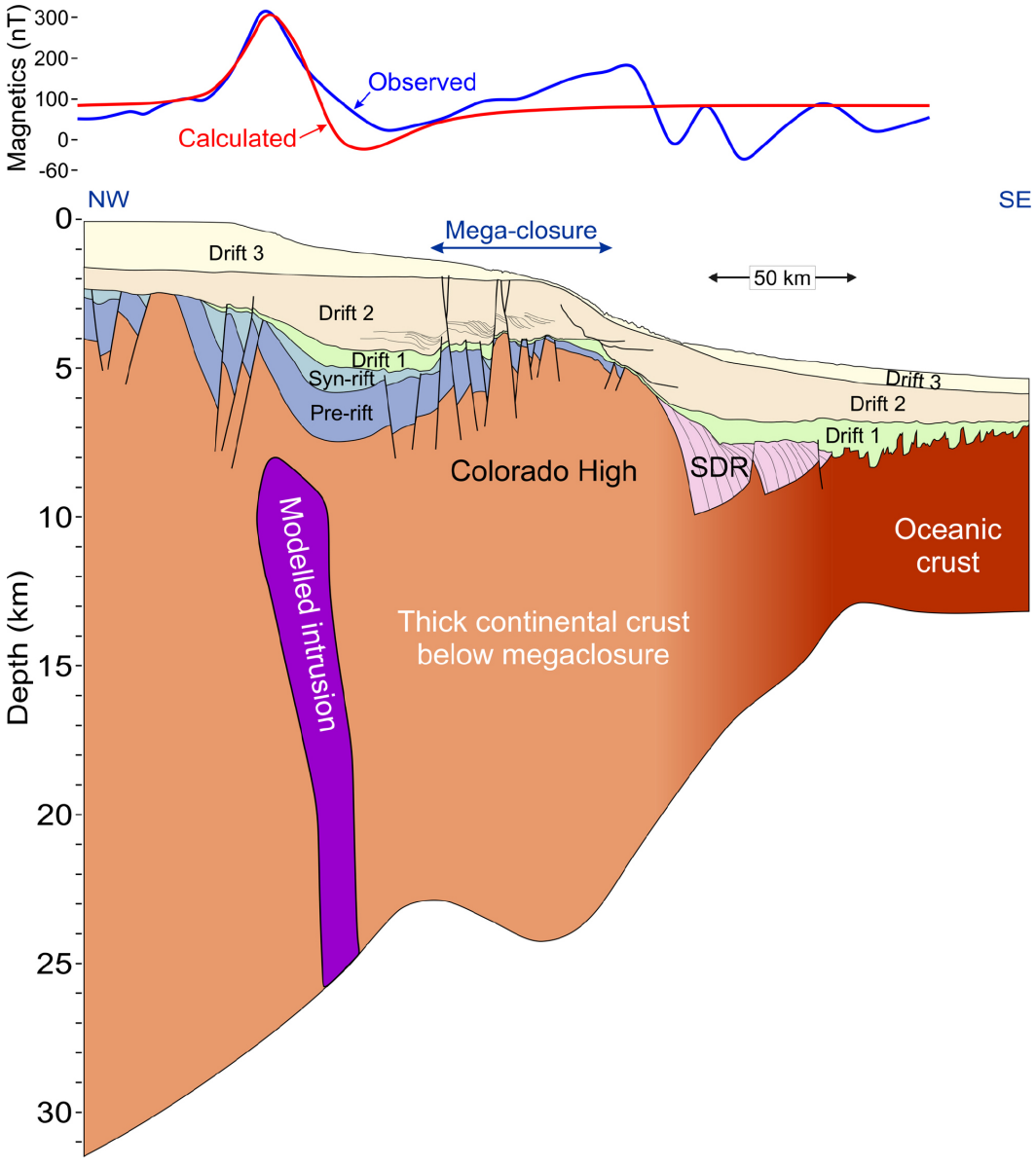


Figure 7. Colorado Basin – Argentine Slope Basin geological cross-section with results of modelling of gravity and magnetic data incorporated.

## CONCLUSIONS

The Colorado High is a large basement high located at the intersection between the Colorado Basin to the west and the Argentine Slope Basin to the east. Based on analyses of the tectono-magmatic evolution of these basins, a geological model for the formation of this highly prospective regional high has been constructed.

## ACKNOWLEDGEMENTS

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