# Santos Basin, Brazil:
Understanding the CO$_2$ exploration risk with ultra-deep seismic

An increasing number of discoveries with high CO$_2$ content offshore Brazil highlight a new exploration risk for the pre-salt play. New seismic data is fundamental to understanding deep geological features to address this risk. CGG's Nebula-C data set provides images down to 20 km in depth and shows ultra-deep crustal features in high definition. Mapping the Moho and deep-seated faults is essential to understanding possible paths of mantellic CO$_2$ migration to pre-salt reservoirs. A de-risking study was performed using Nebula-C to map where the deep-seated faults connect Moho and the reservoir, and where the lower crust is not offset by faulting, allowing prospect identification with lower risk of CO$_2$ contamination.
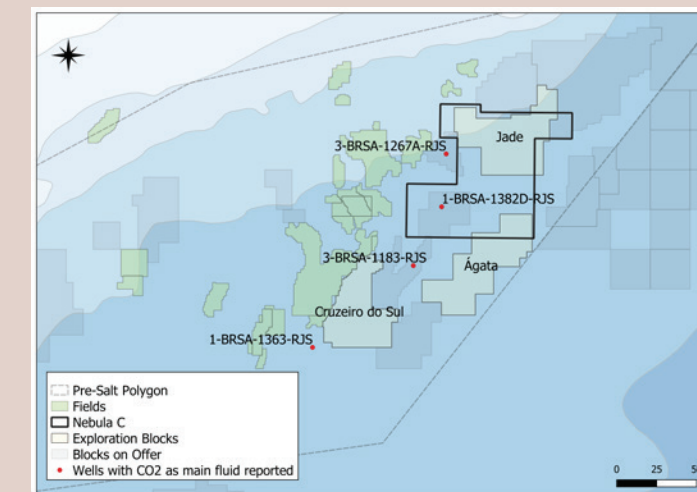
Location of pre-salt blocks in the Santos Basin, the Nebula-C polygon and exploration well results.
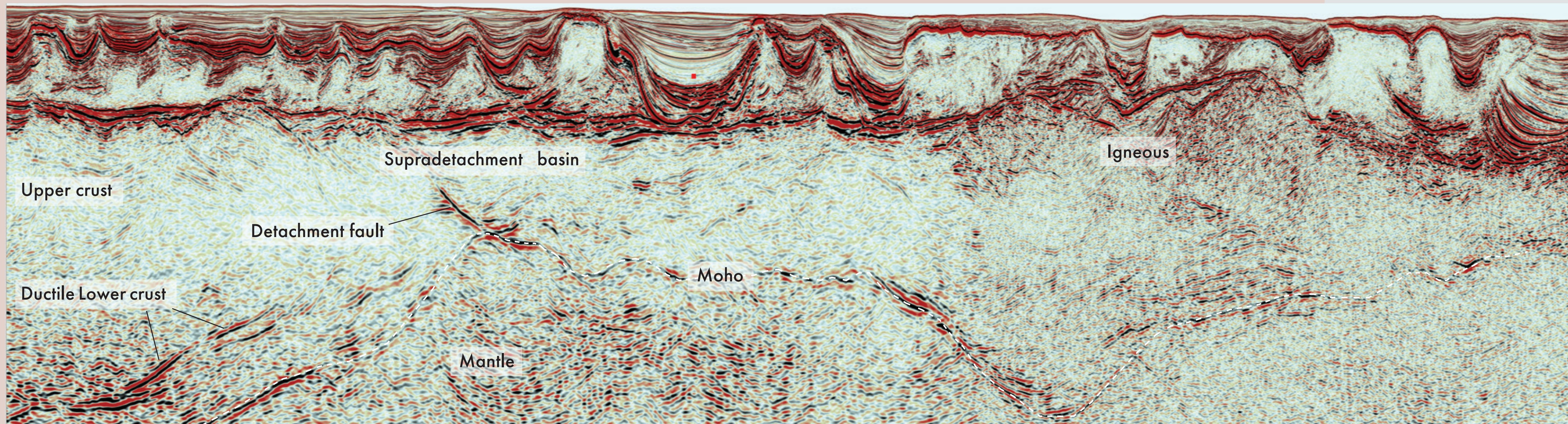
Nebula C seismic section displaying a hyper-extended crust dissected by deep detachment faults extending from the pre-salt sequence down to the mantle. In the region surrounding the upper tip portion of the detachment fault, a high CO$_2$ content was reported in the pre-salt wells.

Santos Basin:
New seismic data helps de-risk CO_2 contamination for pre-salt exploration

CGG's latest imaging technology delivers unprecedented detail of the deep structure in the pre-salt rift basin to support the identification of mantle CO_2 migration pathways, allowing operators to de-risk pre-salt exploration

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THE DISCOVERY of the giant pre-salt fields in the Santos Basin (See foldout map) positioned Brazil among the world's ten largest oil-producing countries. However, recent ultra-deepwater frontier exploration has revealed high carbon dioxide (CO_2) content in some pre-salt oil fields, introducing an important new risk that has undermined the appetite for exploration in this region.

Several studies proposed that magmatic processes and deep crustal faults might act as pathways for CO_2 migration from the mantle to the sediments. The strongest evidence comes from the isotopic composition of the CO_2 analyses in the Santos Basin, which corroborate mantle degassing as the primary origin process. Regions of intense crustal thinning and significant mantle rise, where the crust is dissected by deep faults, show higher mantellic CO_2 content. De Freitas et al. (2022) showed evidence of a structural control on the occurrence of CO_2 concentrations, particularly in the hyperextended regions of the basin, and postulated that mantellic CO_2 reached the pre-salt reservoirs through a deep fault system. These arguments and data supporting the mantellic origin of CO_2 in the pre-salt allow operators to assess the geographic distribution of high CO_2 accumulations.

The scarcity of good seismic images of intra-crustal features and mantle rise has ended with the **Nebula-C 3D survey,** which visualizes the deep crustal structure and Moho with unprecedented detail. Benefitting from the latest acquisition and imaging technologies, it improves our knowledge of the deep structure in the pre-salt rift basin, identifying the structures related to CO_2 migration to pre-salt reservoirs, and enabling an important exploratory risk to be assessed.

NEW NEBULA-C 3D DATA INSIGHTS
For the Nebula-C 3D survey, covering 45,000 km^2, CGG applied its advanced imaging technologies to combine legacy and newly acquired narrow-azimuth towed-streamer (NATS) datasets into a single dual-azimuth (DAZ) image. The aim of the survey design was to improve seismic illumination by using longer cables for enhanced full-waveform inversion (FWI) and an orthogonal azimuth to achieve high-quality images of the sedimentary sequences, deep crust and upper mantle.

The Nebula-C data images the deep structure with the greatest detail to date, bringing greater insight for exploration. The pre-salt comprises regional North-South striking, synthetic, low-angle fault systems that sole either at shallow or deep crustal levels (Figures 1 and 2). The geometry of the intra-crustal structures varies considerably across the area. The detachment faults affect the lower crust (deep detachments) and secondary synthetic fault systems affect the upper crust (shallow detachments), creating uplifted "domed" crustal blocks, known as core complexes that, in specific areas, are exhumed to lower crustal levels (Figure 2). In those regions, the fault crosses the entire crust, potentially facilitating the CO_2 migration between mantle and pre-salt reservoirs. In other areas, the detachment faults sole at shallower levels in the upper crust, limiting migration paths for CO_2 (Figure 1). Additionally, some reactivated detachment faults (Figure 2) may have created pathways for magma ascent during the Upper Cretaceous-Paleogene.

As the structural link between mantle and pre-salt strata varies spatially, CO_2 contamination is not pervasive across the entire distal basin. Both deep and shallow detachment faults can be interpreted in the Nebula-C data. Visualization of the deep crustal architecture is fundamental as it enables the definition of existing pathways between the mantle and pre-salt strata, which is key to de-risking CO_2 contamination in prospective regions.

CONCLUSION
With the recent examples of CO_2-charged reservoirs being encountered by pre-salt wells in the Santos Basin, the ability to de-risk the presence of CO_2 has become crucial. By applying the latest subsurface imaging technologies to newly available long-offset and multi-azimuth data, the Nebula-C 3D dataset can provide clear images of the entire crust and Moho. This has made it possible to map crustal faults and identify faulting style below each prospect and assess the risk of CO_2 contamination. Specifically, we have been able to identify regions of intense crustal thinning with a detachment fault system and pre- and post-salt volcanics with potentially high CO_2 content, as well as areas with a shallower detachment fault system with a lower risk of CO_2. This same mapping workflow can be applied to other areas of the Brazilian pre-salt to enable operators to conduct future exploration with confidence.
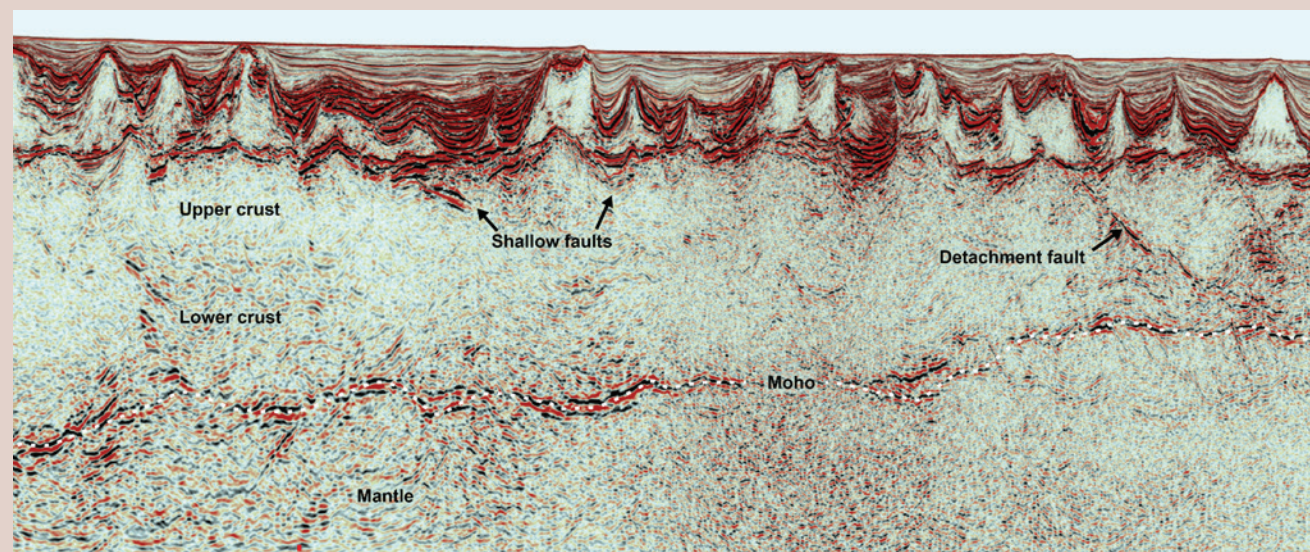
References available online.

Figure 1: Section showing a two-layered crust of constant thickness to the west, preserving the reservoir from a direct pathway with the mantle, resulting in a low-risk area for CO_2 contamination. Eastwards, the faults cut through the entire crust and reach the mantle, configuring a higher CO_2 risk area.
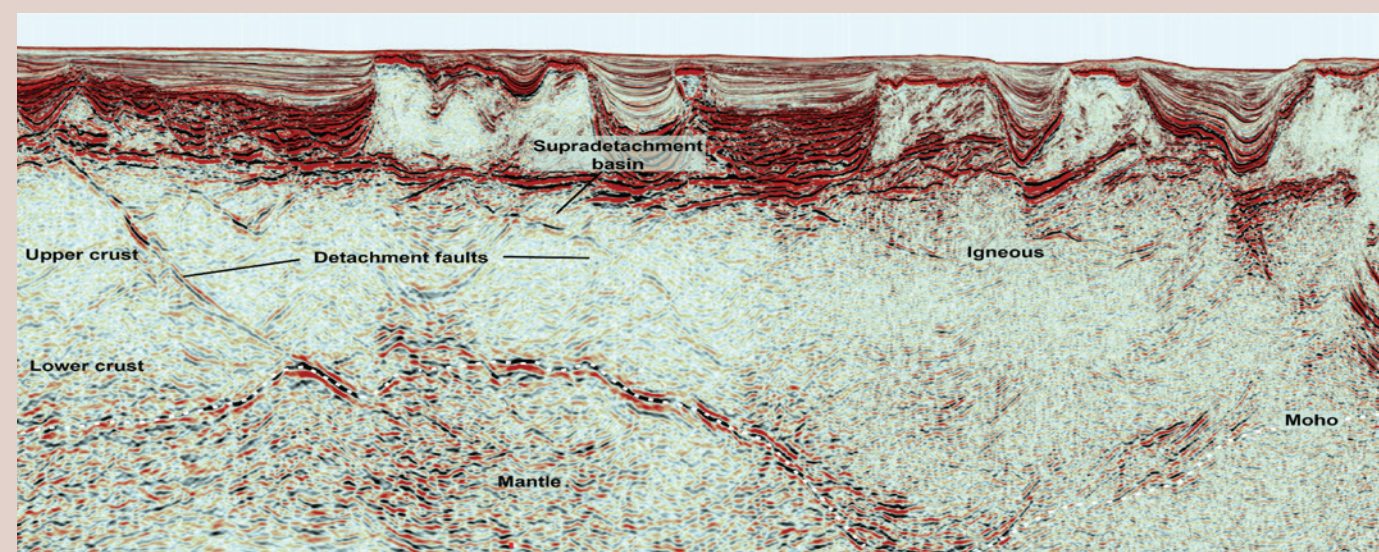

Figure 2: Seismic section displaying an abrupt crustal thinning and deep detachment fault connecting the Moho. In this area, high CO_2 content has been observed in wells. A basement high to the east evidences a large igneous construction on thickened crust.