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Petroleum Mass-Balance of the Neuquén Basin, Argentina: A Comparative Assessment of the Productive Districts and Non-Productive Trends

The effort of eight decades of exploration and development in the Neuquén Basin (west-central Argentina) has identified a EUR of 9.7 BBOE, with a current daily production around 360 MBO and 2.6 BCFG. As result of the de-regularization and privatization process during the 90's, the oil and gas reserves increased within the relatively mature productive tracts (Fig. 1), where the known plays bear around 1.9 BBO and 17.5 TCFG of proven and probable reserves. Additional reserves are expected from testing new play concepts out of the areas under production, as well as from future activities in the under-explored fold belt and from the eastern margin of the basin implanted on the Pampean foreland.

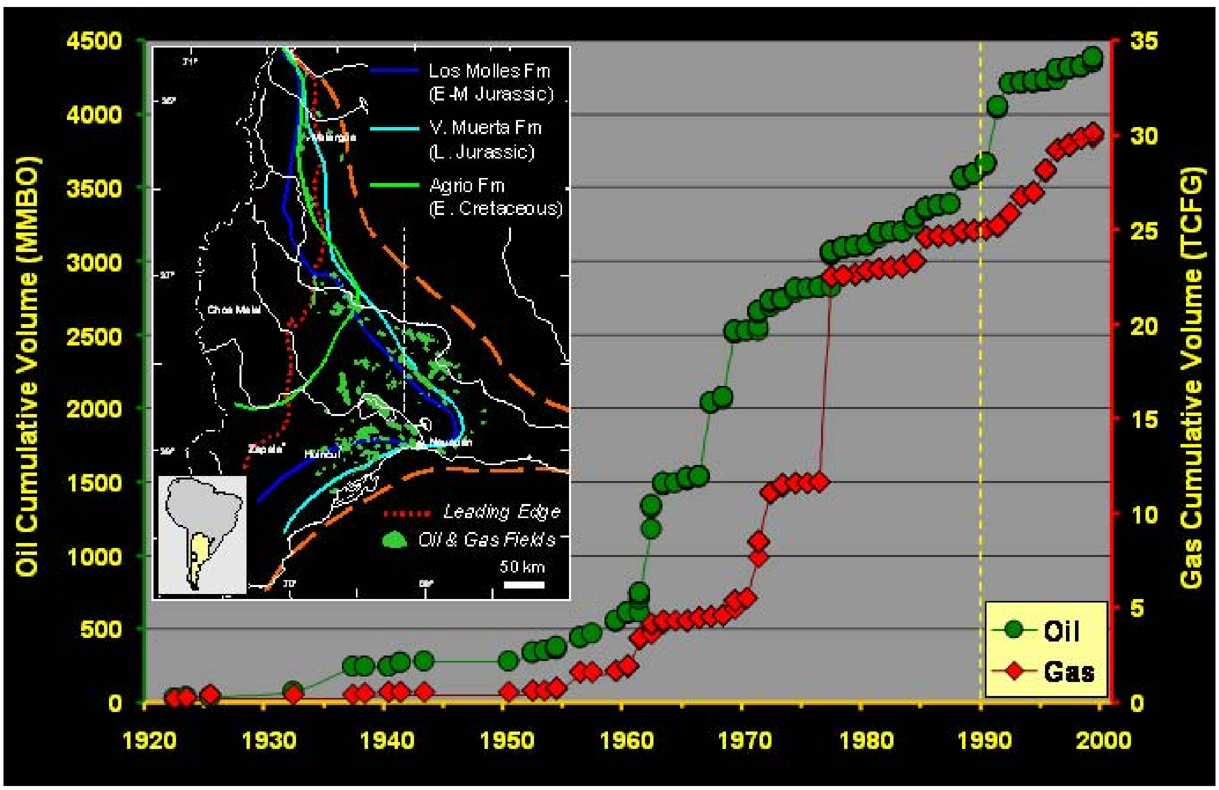

Figure 1. Creaming curve since first discovery in 1923, indicating the latest increment during the 90's due to the establishment of open market rules (yellow dash line). **Insert:** Distribution of hydrocarbon fields within the main productive tract, indicating the eastern updip edge of the three main marine source rocks.

This work focuses on a quantitative comparison of the known productive districts by analyzing the geological elements and the processes involved in the charge, migration, accumulation and preservation of hydrocarbons. The quantification of the generation-accumulation efficiency of the four charge systems, known as Puesto Kauffman and Los Molles (Early-Middle Jurassic), Vaca Muerta (Late Jurassic) and Agrio (Early Cretaceous), along with the geological knowledge of the proven areas, allowed estimating the remaining exploratory potential (Figures 1 and 2).

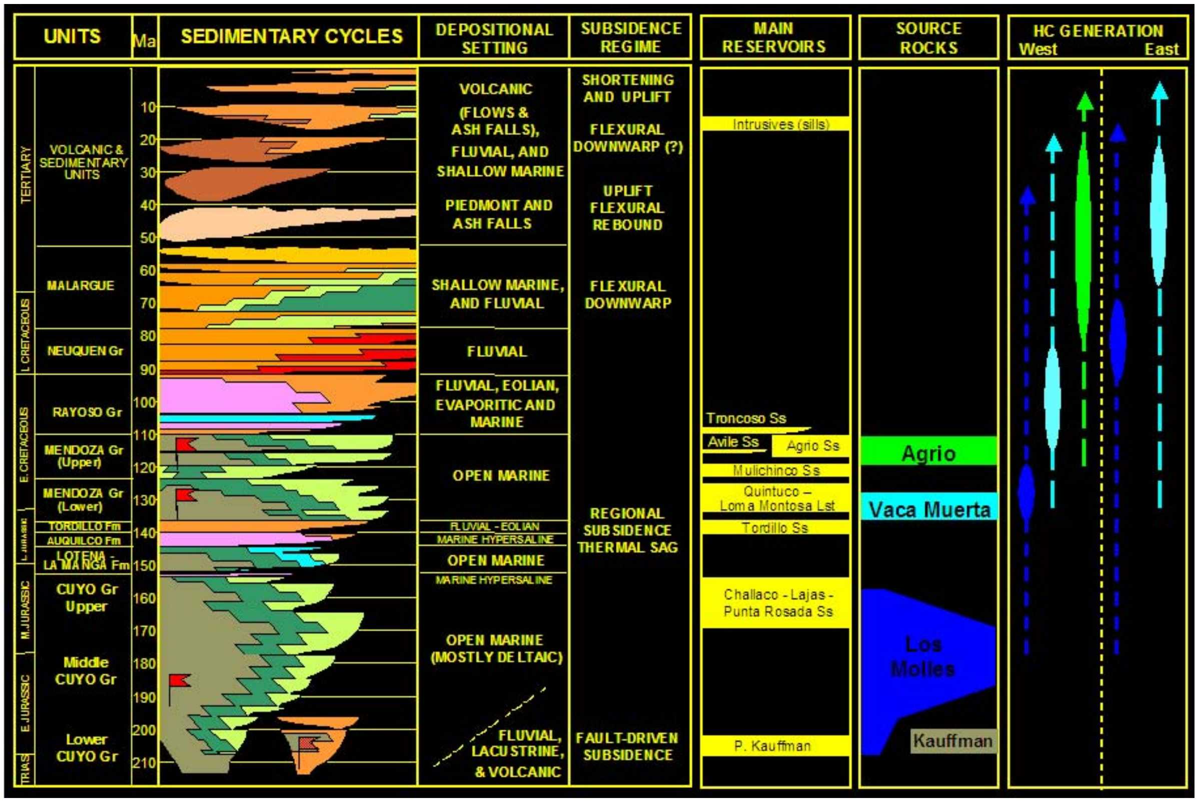

Figure 2. Stratigraphic chart with depositional environments and tectonic evolution of the sedimentary fill in the Neuquén Basin, highlighting main reservoirs and source rock intervals: lacustrine black shales (Kauffman) and marine organic-rich shales (Los Molles, Vaca Muerta and Agrio Fm). A generalized timing of hydrocarbon generation is shown, indicating the stages with strongest rate of kerogen-to-hydrocarbon transformation.

The Jurassic and Cretaceous accumulation took place within a partially enclosed marine back-arc depocenter, implanted on the convergent western side of the South America Plate, linked to the Pacific Ocean. Relative sea level oscillations played a critical role on the development of sources, reservoirs and seals, governed by an extensional tectonic regime. During relative highstands a relatively shallow sea, where organic-rich shales were deposited under sub-oxic to anoxic conditions, occupied the Neuquén embayment. Under shelfal-to-nearshore and fluvial environments, carbonate and clastic high-quality reservoirs accumulated (Fig. 2). Relative low position of the base level drove a very restricted link or complete disconnection with the Pacific Ocean through the magmatic arc. Under this new scenario, the accumulation area dramatically shrunk and the back-arc depocenter became a realm prone to evaporite (seal) and fluvial and aeolian sandstone (reservoirs) accumulation (Fig. 3).

The effects of the Andean compressive deformation of the sedimentary pile started to be noticeable since the latest Paleocene and became very strong during the Neogene (Fig. 2). However, synsedimentary deformation related to old tectonic features, present within the Paleozoic substratum, conducted the creation of structural and combined traps very early in the tectonic evolution of the Neuquén Basin.

Three high quality and thick marine organic-rich intervals cover most part of the basin (Fig. 4). Additionally, an Early-Middle Jurassic non-marine source rock was accumulated within anoxic lakes developed within geographically restricted half-grabens (Fig. 2 and 3). Modeling of the

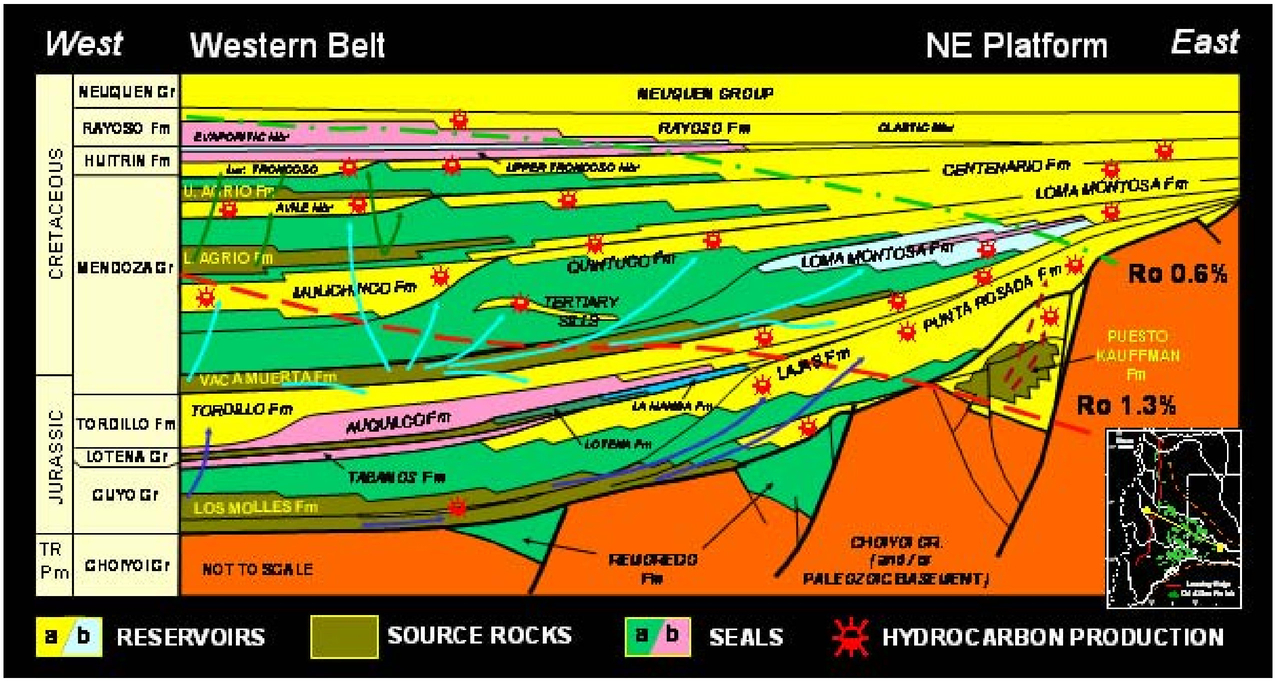

Figure 3. Regional cross-section depicting physical stratigraphy and distribution of proven reservoirs and seals. Present day maturation level and main hydrocarbon charge from different source rock intervals are schematically indicated. Legend: clastic (a) and carbonate (b) reservoirs; clastic (a) and evaporitic (b) seals.

thermal evolution of the Jurassic and Cretaceous marine sources, clearly indicates the existence of several episodes of hydrocarbon generation through the geologic time, particularly along the west-central portion of the basin (Fig. 4, 5 and 6).

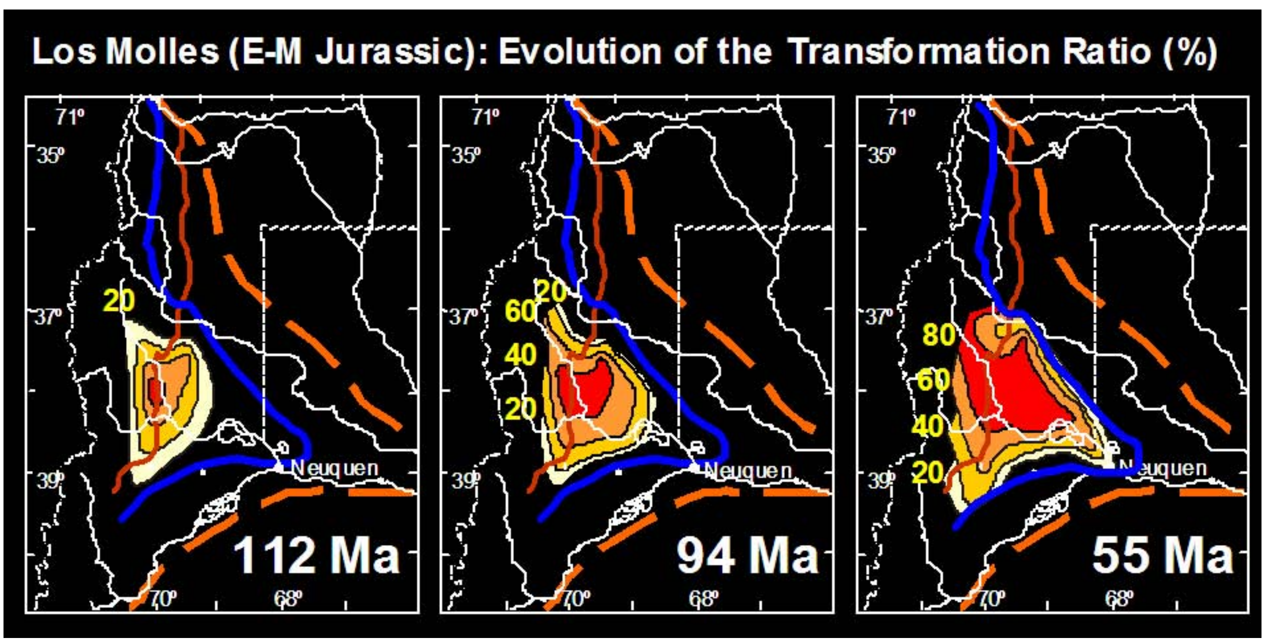

Figure 4. Distribution of the marine Los Molles (Early-Middle Jurassic) source rock (blue line) and the evolution of the kerogen transformation ratios (yellow labels) showing the timing of the different hydrocarbon generation stages.

The overall pattern of the kerogen transformation ratio (TR) maps shown in Fig. 4, 5 and 6 and the trends of Fig. 7 depict the geographic location of the hydrocarbon kitchens of the source rocks through time, and illustrate the final migration from the present deep positions to the basin margins.

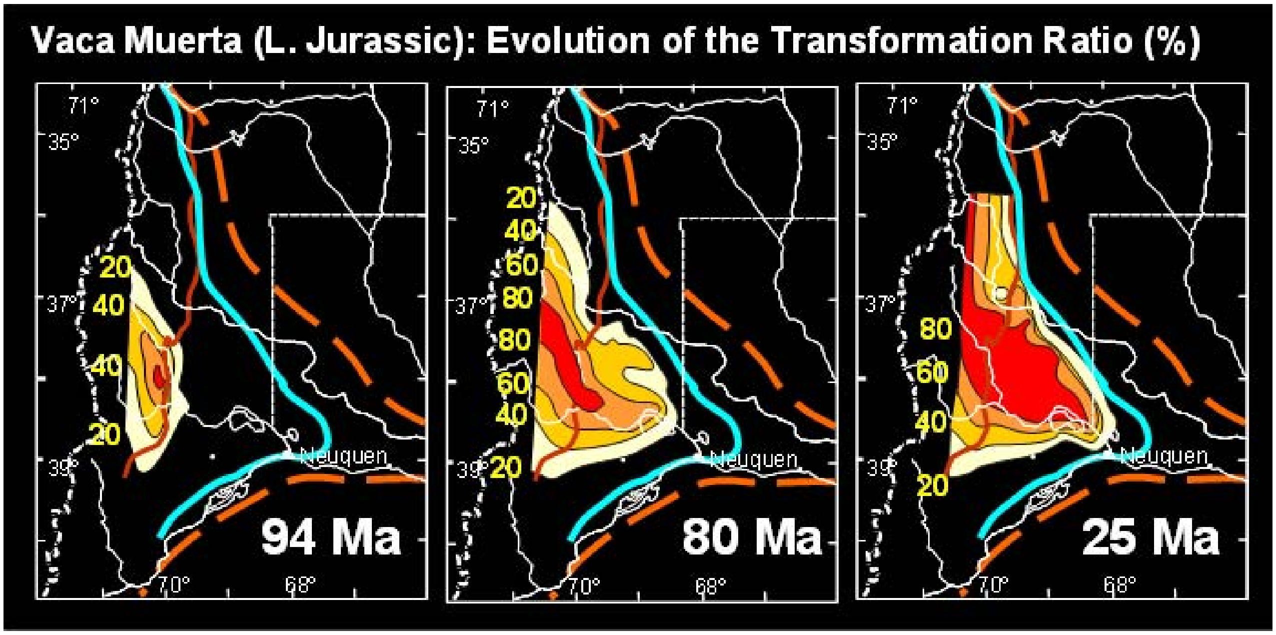

Figure 5. Distribution of the marine Vaca Muerta (Late Jurassic) source rock (light blue line) and the evolution of the kerogen transformation ratios (yellow labels) showing the timing of the different hydrocarbon generation stages.

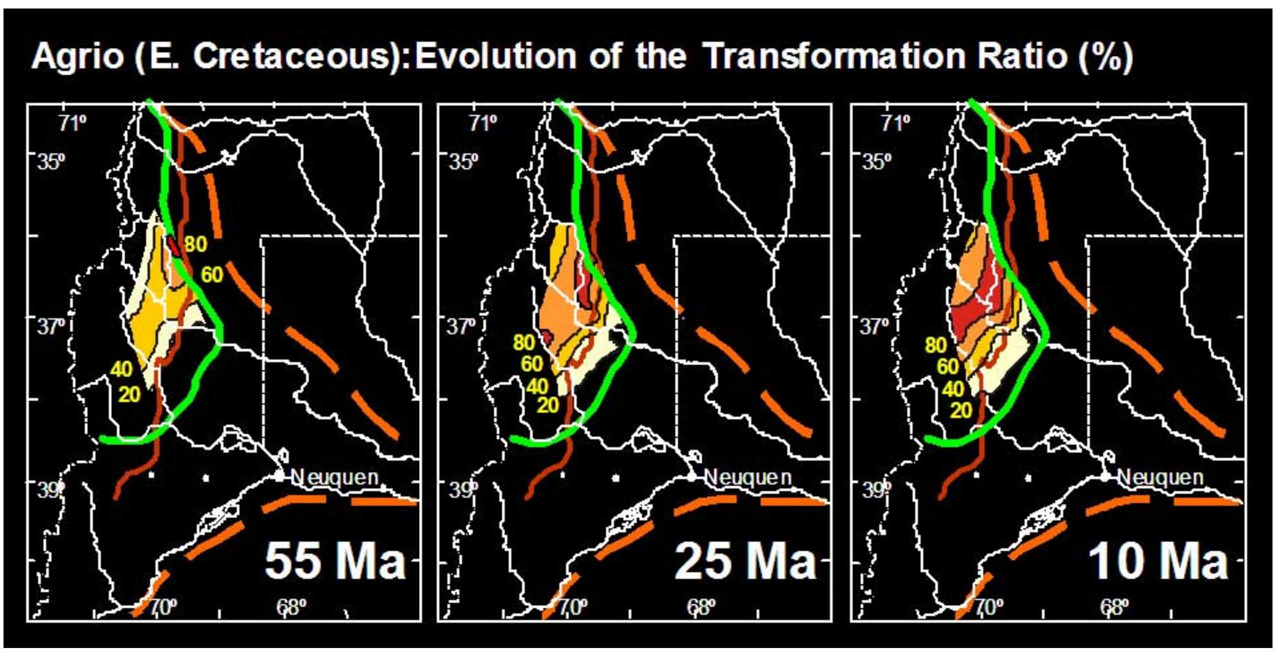

Figure 6. Distribution of the marine Agrio (Early Cretaceous) source rock (green line) and the evolution of the kerogen transformation ratios (yellow labels) showing the timing of the different hydrocarbon generation stages.

The timing of the process critically affected the possibility of hydrocarbon accumulation and preservation. Los Molles source rock developed its almost entire convertibility to hydrocarbons from late Lower Cretaceous to Lower Tertiary times, whereas Vaca Muerta evolved during the Upper Cretaceous and Miocene. The late thermal evolution of Agrio covered the Eocene to Late Miocene. Hydrocarbons generated in the more mature portions of the western area therefore experienced limited chances to be accumulated and preserved in the traps formed during the Tertiary tectonics. This deficient timing strongly disfavored hydrocarbon pools in the current fold belt (Area 1 of Fig. 7), mainly those sourced from Los Molles and Vaca Muerta intervals. Conversely, trap development and adequate timing locally favored relatively higher efficiency along the fringe of the Neuquén Embayment (Areas 2 and 3 of Fig. 7), including the Huincul High area (Area 4 of Fig. 7) where traps were developed through Jurassic and Cretaceous times.

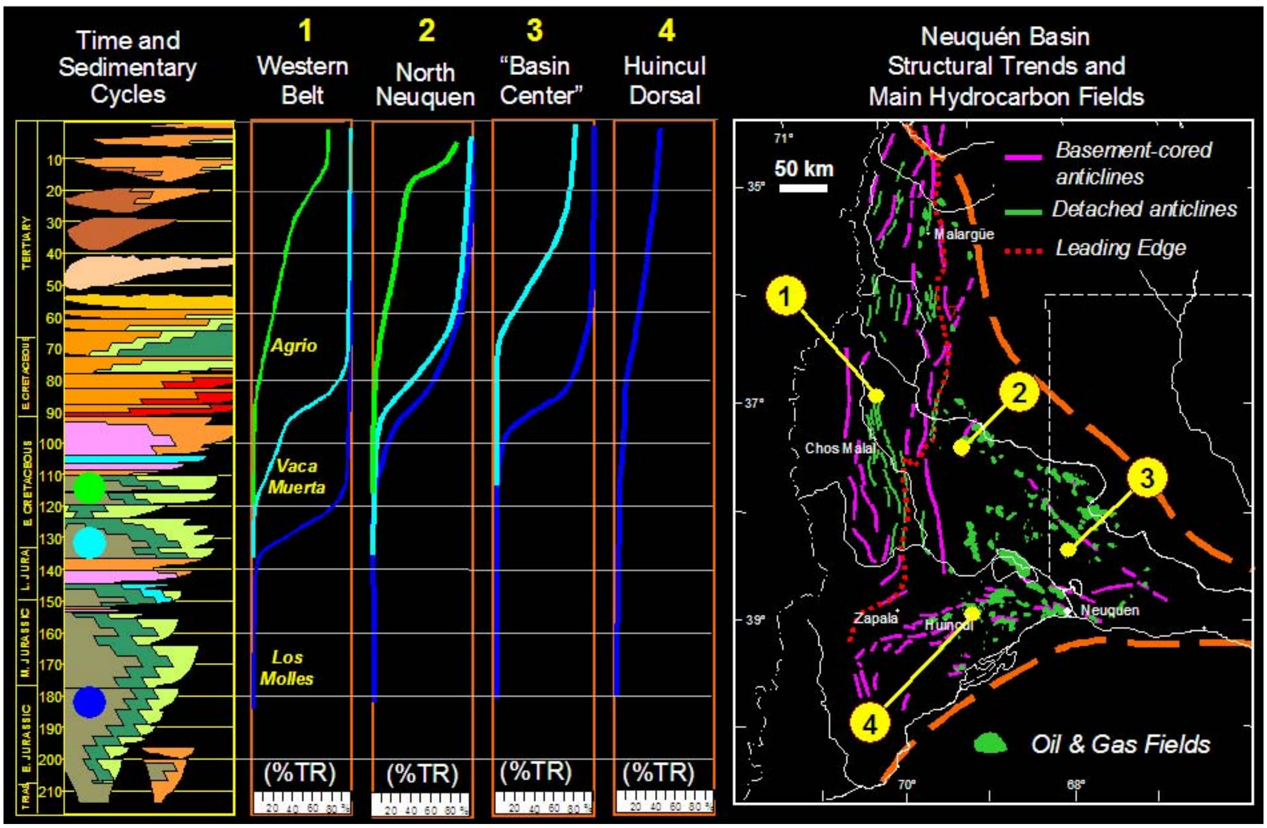

Figure 7. Evolution of the transformation ratio (TR) of the three source rock intervals in the different geological domains.

On a generalized basis and considering the total depositional area of the three source intervals, mass balance estimations are indicative of low generation-accumulation efficiencies at a basin scale. However, when evaluations are performed on the "fetch zone" of the productive districts, each charge system portrays improved efficiencies, in tune with adequate timing of source rock maturation and trap availability.

The aforementioned low efficiency could indicate that most of the hydrocarbons was lost (over 97%), or at least, not preserved within commercially producible accumulations. When the analysis is performed individually in each productive district, the obtained Generation-Accumulation Efficiency (GAE) numbers show some improvement, but the total gap at the base scale is still huge. It is necessary to keep in mind that the potential resources have not been included in the

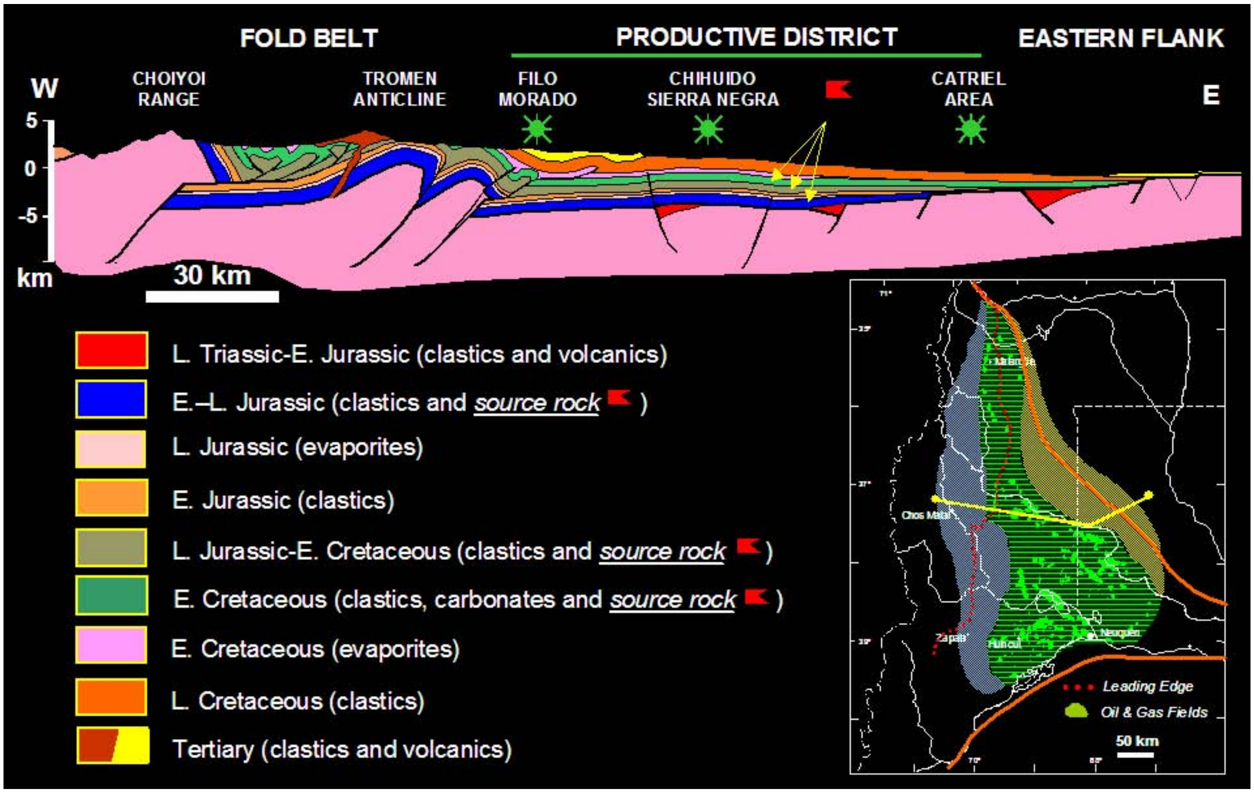

Figure 8. Regional cross-section illustrating the main structural domains across the basin and distribution of the marine source rocks. The inserted map shows the cross-section location and the productive district (greenish area) with oil and gas field distribution. The fold belt is productive in the northern portion of the basin (Mendoza Province) but is mostly non-productive (bluish area). Along the eastern flank of the basin (brownish area) few wells were drilled and found heavy oil. The fold belt and the eastern flank remain under-explored.

calculations, which will affect the final efficiency number. Misunderstanding of the petroleum systems and possible biases in the present play concepts will have a strong implication if the future exploration focus and the final basin efficiency will change, as well. Based only on statistics, the yet-to-find resources are dependent on the knowledge of the producing plays, where hydrocarbon accumulations are dominated by small-to-medium size traps. Likely, additional reserves could be confirmed by re-appraisal of the producing fields. Other areas have geological elements indicating relatively high potential for bigger traps or/and under-explored deeper objectives. Additionally, geological data obtained from exploration wells indicate the presence of an important volume of oil retained/accumulated (?) within the Vaca Muerta basal section (Late Jurassic source rock). Up to now, few wells have had non-commercial production from that overpressured interval in the Neuquén embayment, but these observations turn the testing of a new play encouraging.

Within non- or under-explored areas, big-size pools could be provided by additional future exploration of the less investigated plays, such as in the western thrust belt, where post-mature gas generation may have charged deep reservoirs in big-size structures. Also, hydrocarbon resources can be envisioned within the practically non explored deeply seated traps and basin-center gas systems (Fig. 8). Finally, the potential occurrence of a heavy oil belt in the almost unexplored eastern basin edge is a challenge for non-conventional exploration (Fig. 8). Besides the oil type, difficulties along some portion of this trend are related to poor or lack of information due to the presence of widespread Recent volcanic cover, which is not an unsolvable problem.