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Geology and petroleum systems of the Eastern Meseta and Atlas Domains of Morocco

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Morocco (Maghreb), located in Northwest Africa, has three main structural domains: The (a) Rif Domain, the (b) Atlas Domain comprising two different structural regions, the relatively stable eastern and western Meseta, (characterized by mildly deformed Mesozoic strata) and the active Middle–High Atlas Belts, where the Meso-Cenozoic section was highly folded during the Alpine orogeny; and finally, the (c) Sahara-Anti Atlas Domain at the south, marks the stable margin of the West African Craton. The eastern Meseta, with the Middle and the High Atlas chains (Atlas Domain *ss.*) is the objective of our study; it extends eastward through Algeria. The Middle Atlas and the High Atlas tectonic belts frame the Meseta.

The Cambrian marine transgression over the northwestern African continental platform allowed deposition of shales, silts and sands over a faulted land surface. Folding at the Late Cambrian generated an irregular angular unconformity with the Ordovician sequence. This sequence, dominantly argillaceous at the beginning, ended with a regressive phase of glacio-marine sedimentation that developed coarse sandstones and micro-conglomerate. Volcanic eruptions caused localised metamorphism. The Ordovician ended with regression due to the emergence of the area (Taconic phase). Glacio-eustatism followed, leading to the widespread Silurian deposits of graptolite-bearing black clays in shallow marine, confined (euxinic) troughs. During the Lower and the Middle Devonian, basins developed with flysch deposits. Black shales of Lower Devonian are exposed only in the northeast of the Middle Atlas. The Upper Devonian experienced the transpression and shutting down of the basins. A generalized decollement of the Devonian series seem to have occurred during the Bretonian and the Sudetian folding phases. Nappes of these series are well exposed in the southwest of the Middle Atlas. In the High Atlas, Devonian reef limestones crop out as a carbonate platform.

At Early Carboniferous, the area underwent extension and basin formation along N70° faults. The deposits were mainly marine, giving way to thick, non-marine, conglomeratic and locally coal-bearing intramontane basins in the Late Carboniferous. In the Tendrara Basin, four wells reached the Visean and Namurian, which are composed of black shales, marls with calcareous intervals and volcanic intrusives. In Missour Basin, one well penetrated the Westphalian, represented by alternating beds of conglomerates, micro-conglomerates, silty–sandy shale with thin coal horizons, and the Namurian, represented by shales, silty shales and sandstones. At the end of the Carboniferous, folding and uplifting of the terranes led to erosion and hence, angular unconformity over the whole Morocco. The Upper Triassic sediments begin with a fining upward sequence of basal conglomerates, sandstones, siltstones and shales of fluvial to shallow water environments, submitted to periodic emergences. Missour basin to the West shows more than 636 m of basal sequence in TT-1 well, compared to Tendrara basin to the East with 272 m in TE-1 well. This westward thickening of the basal Triassic sequence could be due to the proximity of Missour area to the source of the continentally derived clastics. In the Late Triassic to Early Jurassic, thick salt with interbedded shales and silts show that the area was more or less closed off from the open sea that periodically supplied with salt water. Regionally widespread and continuous basalt flows lie within the evaporite sequence reflecting the onset of rifting within the Atlas Domain, contemporaneous to the opening of the Atlantic Ocean.

During Early Lias, a marine transgression abruptly changed deposition of lagoonal-clastic sediments to marine carbonates, while some isles remained emerged surrounded with deposits of red clays and anhydrite. During the Middle Lias, the carbonate platform broke down and variable environments with facies deposits changes came into existence: bituminous deep marine limestones alternating with marls suggest that sedimentation took place under more or less euxinic conditions (Issouka Area). Slope deposits, with reef complexes formed along the edges of the Atlas troughs edges. At Late Lias tectonic movement leading to uplift of the western Middle Atlas and the Meseta, while at the same time subsidence occurred in the Atlas troughs. This tectonic

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instability continued through the Middle Jurassic (Aalenian-Bajocian) with more subsidence of the troughs (Boulemane marls) and development of carbonate platform in the Meseta. The end of Middle Jurassic time (Bathonian) is marked by a tectonic uplift and regression of the Tethys towards the north. Continental deposition in the south, deltaic and turbiditic in the north, were interrupted, during the Upper Jurassic, by the emplacement of a carbonate platform.

At Cenomanian the sea invaded the area developing bituminous shales in sub basins, as well as carbonates and sandstones, which were unconformably deposited over the Jurassic sequence. Slow subsidence rate, resulted in thin sedimentary sequences at the close of the Mesozoic Era. Alpine tectonic activity in the mobile atlas belts began to play an increasingly important role in shaping future sedimentary environments.

During the Tertiary, erosion of newly formed relief fed the Neogene basins and the tabular areas depositing conglomerates, siltstones, marls and limestones.

The area was affected by three main orogenic phases:

- Hercynian Orogeny: from Upper Devonian to Carboniferous. The regional compression is related to Gondwana and Laurasia collision. NE-SW and E-W are the main fault trends in the area. Thrust, nappes, granite intrusives, and volcanic extrusives, are the main structural events during this orogeny. In some basins, sedimentation was contemporaneous with folding, creating a series of piggy-back basins.
- During Triassic-Early Jurassic time, Northwest-Southeast extension, related to the formation of the North and Central Atlantic, gave rise to the intra-continental High and Middle Atlas rift trends that appear to be superimposed on Hercynian structural discontinuities. This extensional stress regime also created listric normal faults facillitating long-term subsidence along the margins of the Meseta. Its effect within the interior of the Meseta manifested as macro-tensional gashes (Jebel Missour graben) and minor normal faults. The Middle and High Atlas developed as regional grabens (aulacogens). The Middle Atlas was a mega-tensional gash in the transfer region between two easterly striking sinistral transform faults in Northwestern Africa.
- Late Jurassic to Early Cretaceous time marked the final infilling of the Atlas rift systems. Mild transtensional stresses (associated with oblique left-lateral collision of Northwest Africa and the Iberia Peninsula) may have been the mechanism that initiated movement of the salt. The main phase of post-salt folding and faulting took place, however, during later times when the Atlas domain was experiencing true structural inversion.
- From Early Cretaceous through Tertiary and Quaternary time, the relative motion between Northwest Africa and the Iberia Peninsula changed from oblique left-lateral transtensional to oblique right-lateral transpressional to compressional.

Structural inversion of the Atlas troughs commenced during the Late Cretaceous and continued throughout the Tertiary and Quaternary. The Meseta and the west of the Middle Atlas behaved as stable blocks and were thus only slightly affected.

Reactivation of normal faults and decollement within the salt and salt movements were the main responses.

Two petroleum systems were defined in the Atlas Domain *sensu stricto*:

- The Palaeozoic-Triassic Petroleum System, where the source rock could be of Silurian, and/or Carboniferous age. The Silurian source rock, as encountered in the Tadla basin, is represented by type II–III but dominantly type II hot shales (known by their high Gamma Ray Response) which range from immature to overmature states. The Namurian shales in the Meseta (Missour and Tendrara basins) are marginally mature to overmature. The Westphalian source rock, encountered in the Missour basin has TOCs between 1% in the shales and 79% in the coals. The S2 is higher than 5 mg/g and the maturation rate is within oil window. The different stages of maturation registered in both the Carboniferous and Silurian are due to the complexity of structuration (thrusting, underthrusting), hot spots, granite intrusion and difference of subsidence rates half grabens compared to those in the ponded basins, and other factors.

The main reservoirs are the basal Triassic and Carboniferous clastics sealed respectively by salt and shales. Traps are mainly structural for the Carboniferous and structural and stratigraphic for the Triassic.

- The Jurassic Petroleum System is characterized by Lower Jurassic (Domerian) rich, marine type II source rock. Lower Lias carbonates and Dogger sandstones and carbonates represent the reservoirs. Traps are structural, formed contemporaneously with the Atlas Tectonic Inversion, and stratigraphic (reefs). They could be attractive in the area because, wherever adequately explored in Morocco, oil and gas was produced from these reservoirs. Even though the Jurassic is outcropping, production of oil and gas occurred in various

compartmentalized Jurassic intervals, ranging from Domerian to Toarcian and Dogger, in the pre-Rif ridges of the Rif Domain.