AN INTEGRATED STUDY ON HYDROCARBON GENERATION AND MIGRATION PATHWAYS OF SOUTHERN SINDH MONOCLINE, LOWER INDUS BASIN, PAKISTAN

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ABSTRACT

The Early Cretaceous Sembar Formation represents one of the most significant petroleum source systems within the southern Indus Basin of Pakistan. This work integrates three key investigative components of these source rocks in the lower Indus Basin. i.e., their geochemical characterisation, reservoir potential assessment, and petroleum system modelling, with the aim to comprehensively evaluate the hydrocarbon prospectivity of the Sembar Formation. A detailed geochemical and petrographical analyses were undertaken using total organic carbon (TOC), biomarker proxies, mineralogical data, trace elemental composition, and kerogen microscopy from the 17 well cuttings across four exploration wells (Sher-01, Jumman Shah-01, Buzdar South Deep-01, and Bhadmi-01). The TOC values ranged from 0.76 to 3.07 wt. %, indicating organic-rich facies. The microscopic and biomarker data revealed a mixed organic matter input, mostly of marine origin (i.e., phytoplankton algae) with subordinate terrestrial contributions, deposited under anoxic, non-sulfidic conditions with moderate stratification and warm, humid climatic settings. These conditions, intensified by upwelling systems, enhanced marine bioproductivity and organic matter preservation, favouring organic carbon accumulation. The second component focused on the shale's reservoir quality and gas potential through integrated geochemical, mineralogical, petrophysical, and basin modelling analysis. TOC values extended to 3.07 wt. %, with hydrogen index (HI) values ranging from 47 to 463 mg HC/g TOC. Vitrinite reflectance (0.56–1.23 %Ro) and transformation ratio (TR) up to 86% confirmed thermal maturity within oil and wet gas

windows. Authigenic microquartz, forming amorphous to euhedral aggregates, contributes to the high brittleness index (i.e., 0.85–0.98), which, along with microfracture networks, renders the Sembar Shale mechanically favourable for hydraulic fracturing. Porosity is primarily interparticle, intraparticle, and non-fabric fracture-related. Basin modelling confirmed the conversion of oil to gas in deeper stratigraphic intervals during the Early Oligocene to present, supporting the potential for shale gas exploitation in deep burial zones.

The third component utilised 2-D petroleum system modelling by integrating seismic interpretation, geochemical data, and geological framework to determine the temporal evolution of hydrocarbon generation, migration, and accumulation. The modelling revealed that the Sembar Shale reached the main oil window between 90 and 60 Ma and thermogenic gas generation has persisted since the early Paleocene. Hydrocarbons migrated laterally into the Sembar sandstone and subsequently into the overlying Goru Sandstone through microfractures and fault systems. The Goru Formation's limestone and shale units act as regional seal rocks, facilitating the entrapment of commercial oil and gas accumulations. This work confirms that the Sembar Shale possesses the essential geochemical richness, thermal maturity, and mechanical characteristics for both conventional and unconventional hydrocarbon exploitation and as such provides the first holistic characterisation of the Sembar source rock system, establishing a benchmark for shale reservoir evaluation in the region. It underscores the necessity of integrating petrographic, geochemical, and modelling workflows to accurately assess shale prospectivity in frontier basins. The results hold broad implications for the development of unconventional petroleum resources across the Indus Basin and analogous depositional environments globally.

Key words: Basin modelling; Hydrocarbon exploration; Organic geochemistry; Reservoir characterization; Sembar Formation; Thermal maturity.

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