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New Paradigm in Himalayan Foreland Exploration: Challenges and Opportunities*

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Abstract

The Indo-Eurasian Plate collision, which commenced from Lower Eocene, and its continued convergence along northern margin of Indian Plate has initiated development of peripheral foredeep/Himalayan Foreland on the leading underthrust Indian Plate. Tertiary sedimentation started in the foreland in front of the rising mountain province of the Himalaya over a peneplained base comprising of Proterozoic sediments. Himalayan Foreland sediments (Himalayan Foothills - HF) are exposed in fold thrust belt between Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT); and in subsurface extend craton-ward below the Ganga Basin (GB) alluvium ([Figure 1](#)).

Foreland basins have been the target of hydrocarbon exploration since the early days of the oil industry and around 50% of global recoverable hydrocarbon reserves are contained in traps within foreland basin setups. The Indian Himalayan Foreland Basin always remained an exploratory targets. Its first exploratory well was drilled in 1954 to chase the gas seep in the Kangra Recess from Neogene sediments in Jwalamukhi Temple. Subsequently, extensive surface and subsurface data was acquired in the Himalayan Foothills and Ganga Basin to establish the Tertiary/Neo-Proterozoic petroleum system elements.

Petroleum Exploration

In the HF, considering the petroleum system certainty level (Magoon and Dow, 1994), a hypothetical Tertiary petroleum system has always remained the main exploratory target. In Kangra Recess of HF, Palaeocene-Lower Eocene marine Subathu unit has been considered as prime source rock, whereas Upper Oligocene-Lower Miocene transitional clastic sediments of Dharmshala and Mid-Miocene-Pleistocene fluvial molasse sediments of Siwalik are the main reservoir. In spite of thermogenic gas occurrence reported in wells from Tertiary sequences and a

number of gas seeps and oil shows in Himalayan Foreland, a commercially viable petroleum system could not be established. Despite scanty and fragmented data, an integrated approach using well, source rock, gas and oil seeps data were re-examined and source rock correlation has been attempted for ascertaining the presence of alternate petroleum systems and effectiveness of Tertiary petroleum systems.

Based on surface geology and drilling results in HF and GB, two litho-assemblages accredited to pre-collisional and syn-collisional history of the Himalayan orogeny have been established. Pre-collisional Neo-Proterozoic sediments belong to platformal limestone/dolomite and clastics of Bilaspur, Shali, Shimla, Krol, Ujhani, Tilhar, and Karnapur formations, whereas syn-collisional sediments belong to marine Subathu sediments, transitional clastic Dharmshala, Murree, and Matera sediments and Siwaliks molasse sediments. Litho-assemblages, drilled well data, source rock, oil and gas seep data of the Proterozoic northern Indian craton hosting Vindhyan, Ganga, and Bikaner-Nagaur basins and HF has been studied to understand the possibility of Proterozoic hydrocarbons and its effectiveness in the Northern Indian Craton.

In HF, tectono-stratigraphically two Tertiary belts viz. Lower Tertiary belt (Paleocene-Early Middle Eocene Subathu Formation and Upper Oligocene-Lower Miocene Dharmshala/Murree Formation) and Upper Tertiary belt (Mid-Miocene-Pleistocene Siwalik Formation) are demarcated between MBT and HFT (Thakur, 2010). The Lower Tertiary belt outcrops between MBT and Main Boundary Fault (MBF; also known as Riasi Thrust in Jammu, Palampur Thrust in Kangra, Bilaspur Thrust in Simla Hills and Nahan Thrust in Sirmur). This belt litho-stratigraphically is comprised of discontinuous bodies of stromatolite bearing Proterozoic limestone which represent the basement over which the Lower Tertiary sediments were deposited. The limestone basement with its cover was thrust along MBF over the Upper Tertiary belt of Siwalik group. In HF, Upper Tertiary belt outcrops between MBF and HFT and extend further south below the Ganga Basin alluvial plain towards flexural bulge ([Figure 1](#) and [Figure 2](#)).

In HF, well HF-A, HF-B and HF-C have flowed gas from Dharmshala and Lower Siwalik sequences, while in Ganga Basin only two wells, GB-A and GB-B, located in Madhubani and Gandak depression respectively have given gas shows and oil indication from Tertiary (Lower Siwalik) core. However, it is the Neoproterozoic sequence that has given number of oil and gas indication in wells of the Sarda and Gandak depressions.

In the Kangra Recess, envisaged source rock, i.e. Subathu at surface and subsurface, indicates very good organic matter richness and hydrocarbon generation potential but Tmax (425-434°C) data indicates that source facies has not matured to expel hydrocarbon, and Siwalik sediments in Kangra Recess also show poor organic matter richness. In the Ganga Basin, Tertiary sediments in wells GB-C and GB-D of the Sarda Depression possess fair to very good organic matter richness (TOC: 0.83-5.66%) and very good hydrocarbon generation potential (S2: 2.25-4.02 mg HC/g rock) but Tmax data of both the wells (429-435°C) indicates immature organic matter. 1D Burial history curve of well GB-C also indicates the immature Tertiary source ([Figure 4](#)). Maturity modeling of well GB-C in the Ganga Basin reveals that source rock layers present in Neo-Proterozoic formations have reached maturity of early to main window of oil generation ([Figure 3](#)).

In the northern Indian Craton only two live non-biodegraded surface oil seeps have been reported and analysed, i.e. from Proterozoic Vindhyan Basin and near MBT in Kangra Recess, both samples were compared with the established Neo-Proterozoic heavy oil of Baghewala Field from Bikaner-Nagaur Basin. Biomarker studies like Pr/Ph (1.03-1.56), C29H/C30H (0.9-1.2) and C35H/C34 (0.9-1.08), presence of C29 $\beta\beta$ and

Sulphur content (1.8%) indicates marine oil sourced from Late Precambrian strata deposited in an anoxic environment of carbonate/mixed carbonate-siliclastic sourced oil, indicating that both the seeps and Baghewala heavy oil are geochemically alike or genetically correlatable ([Figure 4](#)).

Stable Carbon Isotopic values of $\delta^{13}C_1$ (-28 to -33 ‰) of the gas samples collected from well in Tertiary sequences of Kangra Recess, HF and Proterozoic sequences of Ganga Basin (Karnapur Formation) shows similar maturity indicating the possibility of common source for Tertiary and Proterozoic gas ([Figure 5](#)). It is possible that gas encountered in HF and Ganga Basin may have migrated from a Proterozoic source.

Conclusions

From the above observation it can be inferred that the Neo-Proterozoic platform carbonate/mixed carbonate-siliclastic source may have generated hydrocarbon which remained pooled in deeper complex strati-structural Proterozoic and Tertiary traps. Neo-Proterozoic carbonates associated with Lower Tertiary belt between MBT and MBF may provide a Neo-Proterozoic play at shallower depth as a primary exploratory target, thus necessitating a shift in focus from Tertiary exploration model to Neo-Proterozoic exploration model in Kangra Recess of Himalayan Foothill.

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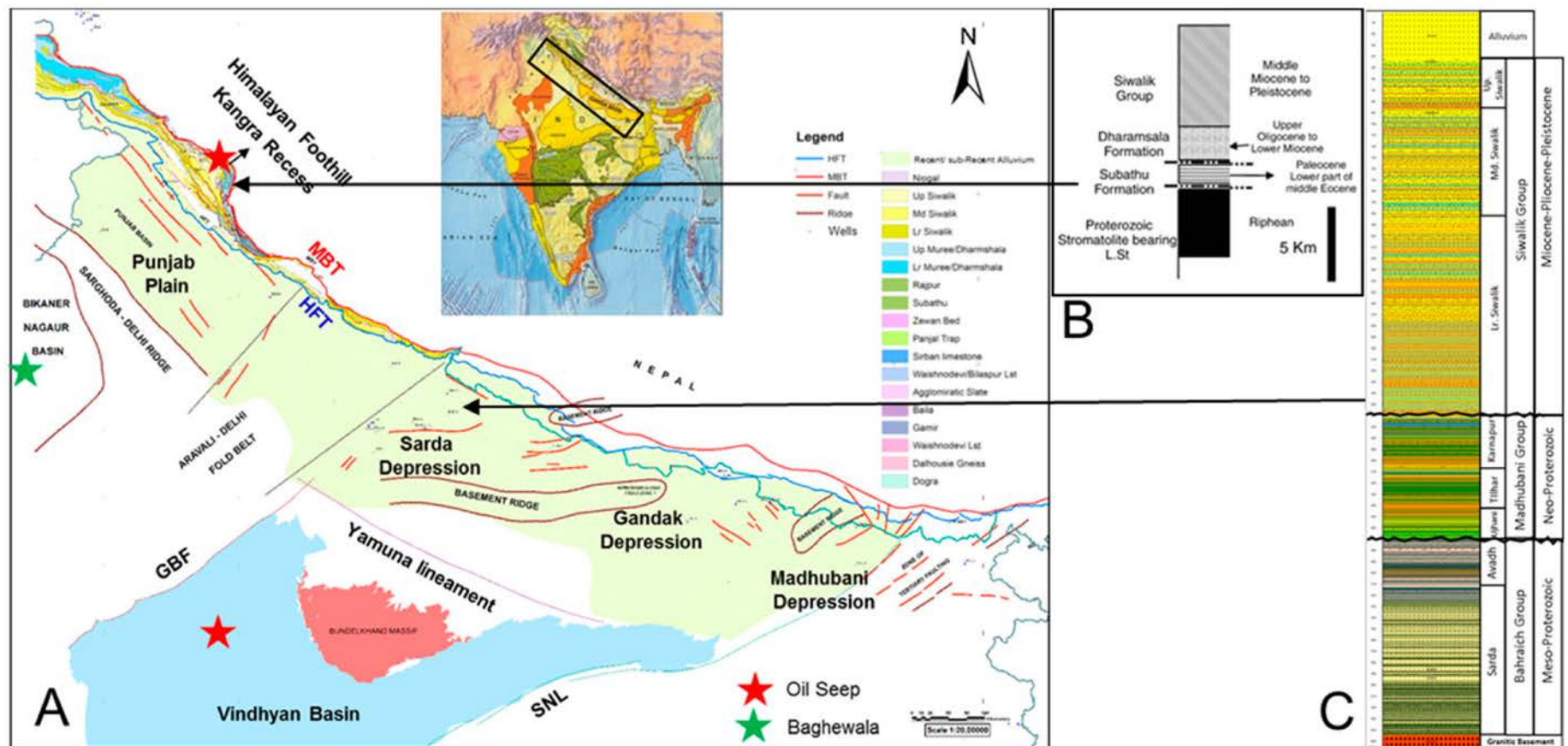


Figure 1. (a) Tectonic map of Himalayan Foreland Basin, showing positions of Himalayan Foothills and Ganga Basin with respect to Vindhyan and Bikaner-Nagaur basins (modified after British Petroleum, 1991). (b) Composite stratigraphic column of the Himalayan Foothill (Thakur, 2010). (c) Composite stratigraphic column of Sarda Depression, Ganga Basin.

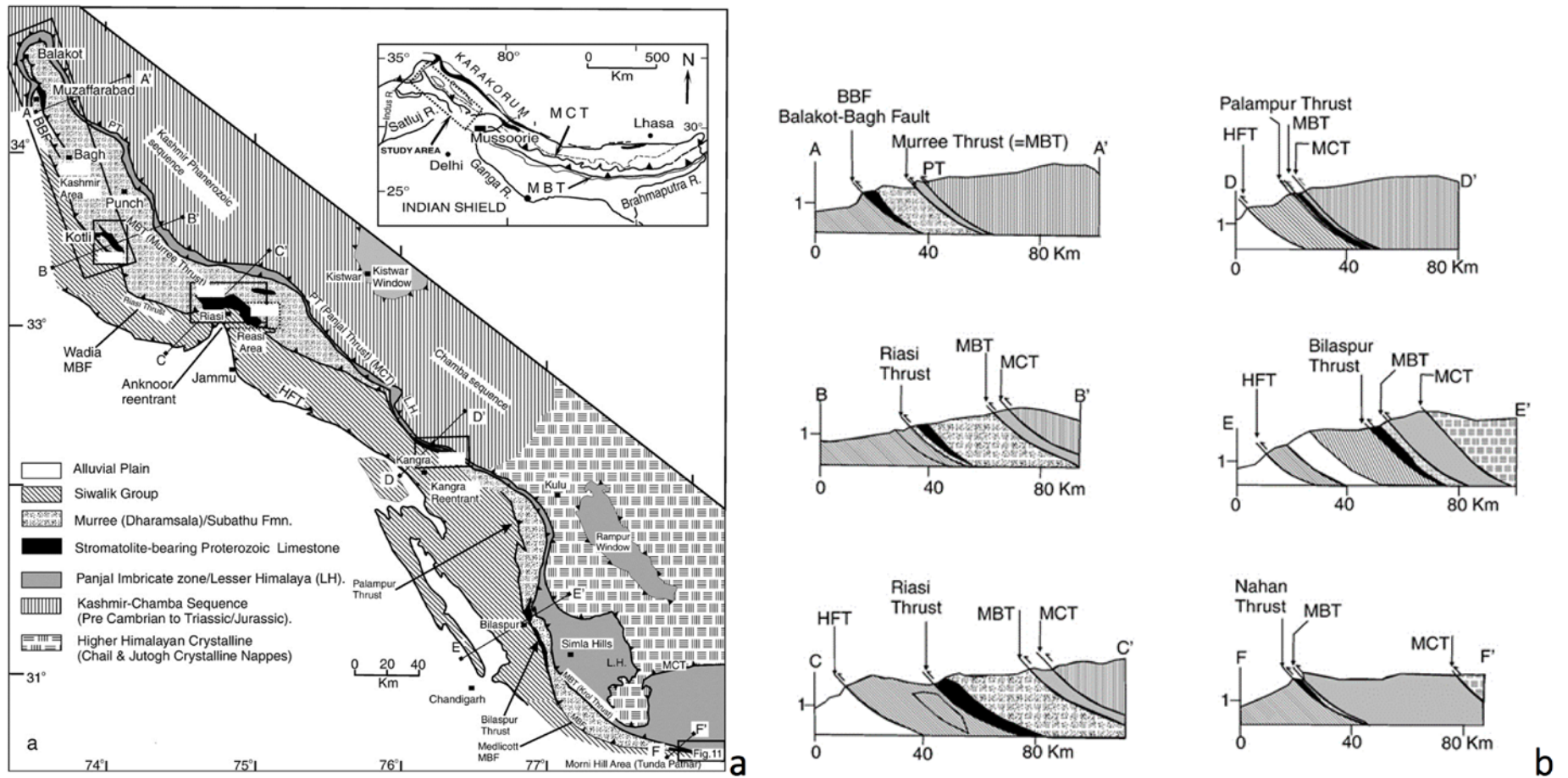


Figure 2. (a) Outline tectonic map of the northwest Himalaya and adjoining regions showing regional framework of Lower Tertiary and stromatolite-bearing Proterozoic limestone inliers zone. Inset rectangles are locations of Proterozoic limestone inlier zones (Thakur, 2010). (b) Cross-sections illustrating position of thrust MBF and MBT and stromatolite-bearing limestone on its hanging wall. Locations: marked as solid lines (A-A' to F-F') across squares in [Figure 2a](#).

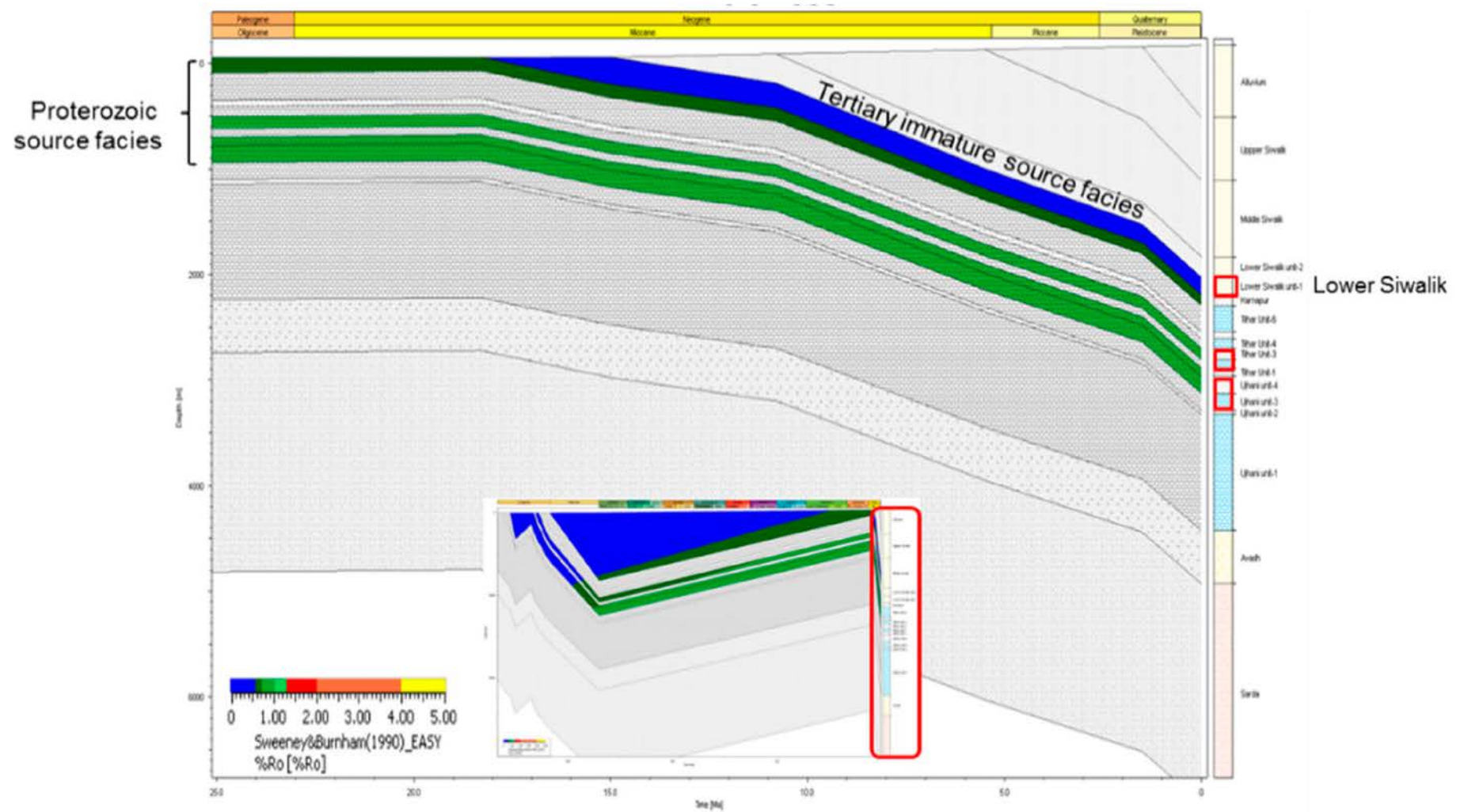


Figure 3. Burial history with maturity overlay of well GB-C, Sarda Depression, and Ganga Basin.

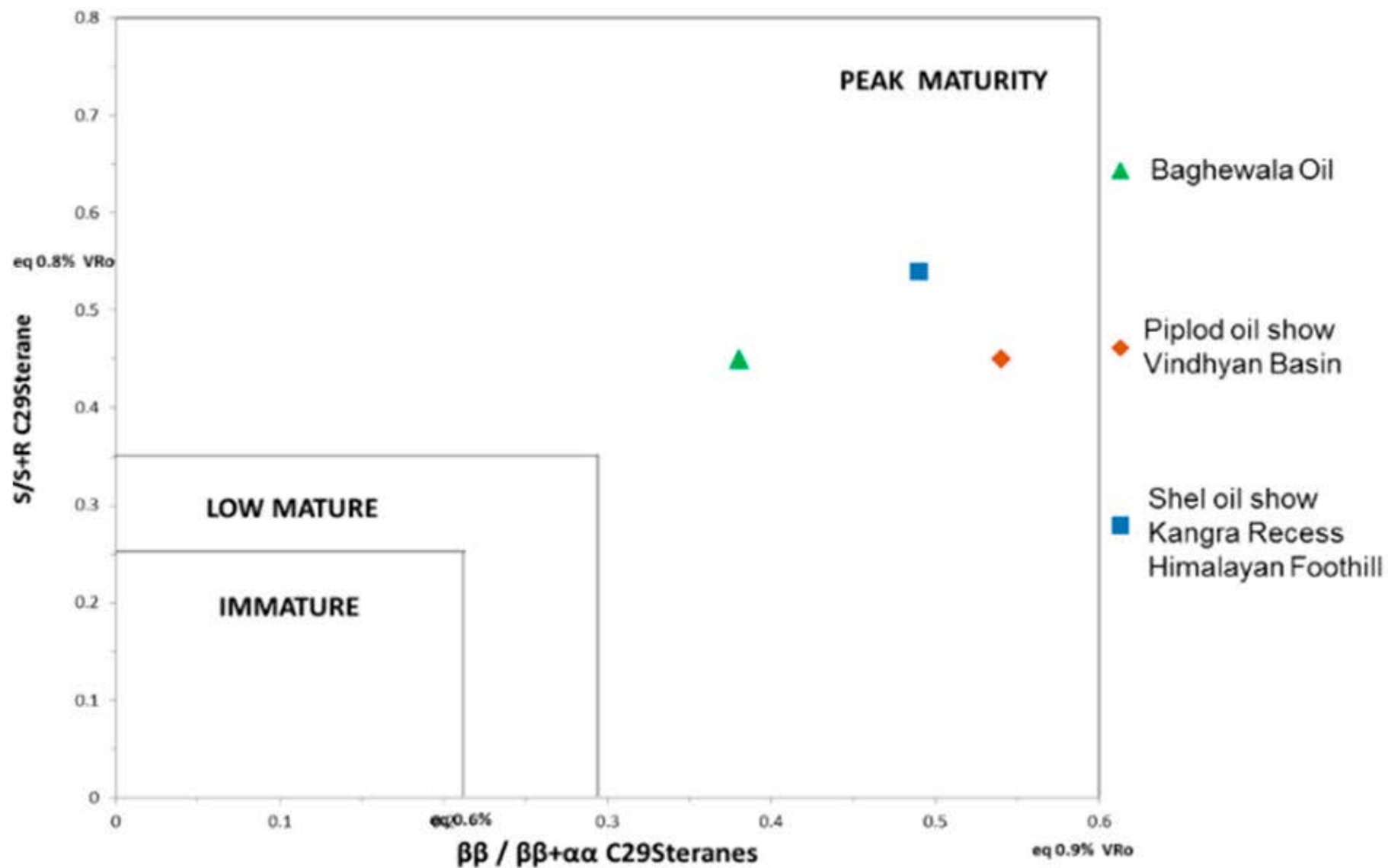


Figure 4. $\beta\beta / \beta\beta + \alpha\alpha$ C29 steranes vs $S/S+R$ C29 sterane plot of Baghewala oil, Chambal (Vindhyan) and Kangra Recess (Sub-Himalaya) oil seeps.

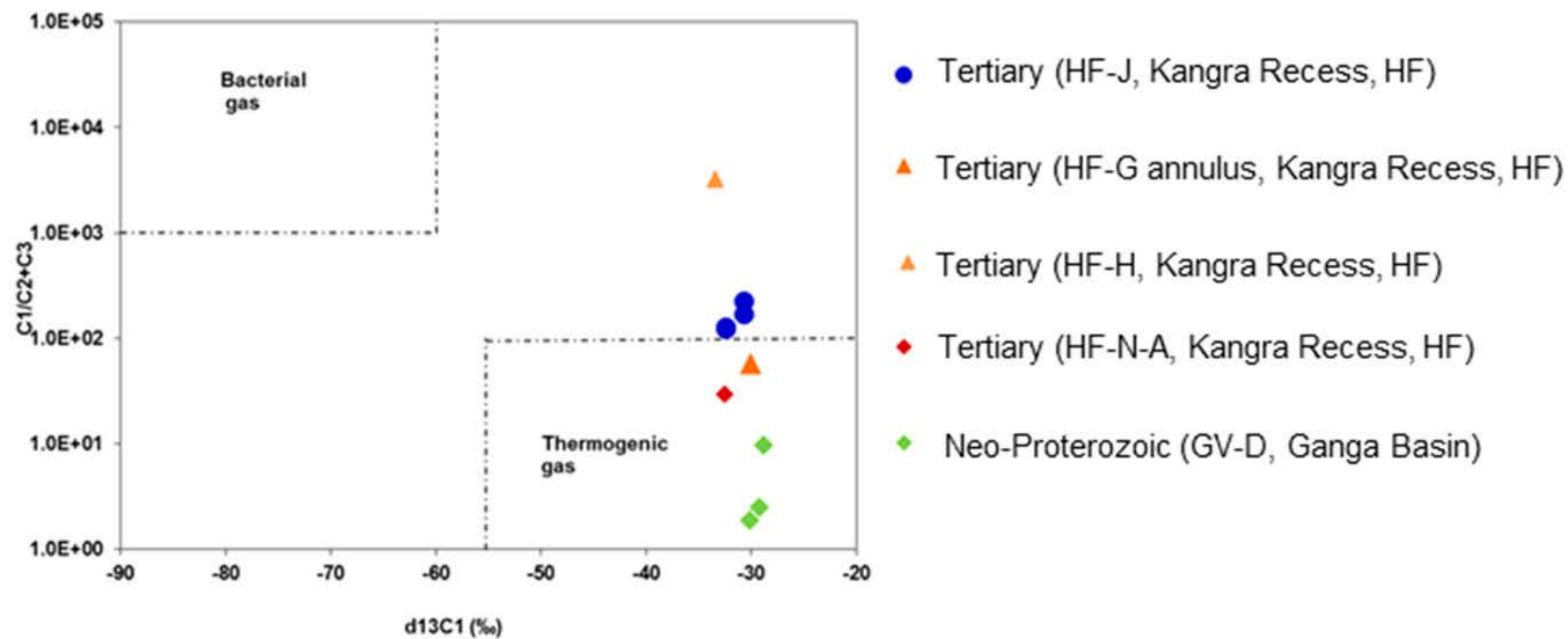


Figure 5. Stable carbon isotopic values of $\delta^{13}C1$ of the gas samples collected from Tertiary sequences of HF and Proterozoic sequences of Ganga Basin.