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RECENT DEVELOPMENTS IN PROTEROZOIC-MESOZOIC SUCCESSIONS OF THE NORTHWEST HIMALAYA

PROTEROZOIC-PHANEROZOIC PETROLEUM SYSTEMS

The Himalayan orogeny has shaped the sedimentary basins of the Northwest Himalaya. Himalaya represents a potential prospective region for hydrocarbon exploration. Within this region continuous tectonic deformation has formed both ‘conventional’ and ‘unconventional’ petroleum systems at multiple stratigraphic levels of Precambrian to Neogene age (Fig. 1). The Proterozoic Sirban Limestone Formation (SLFm) exposed in a number of inliers in Jammu, is a potential target for hydrocarbon and ore mineral exploration. The structural complexity not only makes correlation of the SLFm with coeval hydrocarbon producing Proterozoic formations in the neighbouring Salt Range in Pakistan and elsewhere in the world extremely difficult, but also limits the understanding of genesis of the mineral deposits. The base of the SLFm inliers is not exposed anywhere in the region and the age of this sequence is believed to range from Palaeoproterozoic to Neoproterozoic. Recently important age diagnostic palynomorphs have been recovered from different sections of the SLFm (Bhat et al., 2009). To place the palynomorph bearing intervals into stratigraphic order is important for correlation of these sections. However, structural complexity and the monotonous nature of the lithology limit the scope for correlation. This problem can only be resolved by geochronology and dating of the important marker horizons in the SLFm. In the absence of tuff horizons Rhenium (Re) – Osmium (Os) geochronology data can

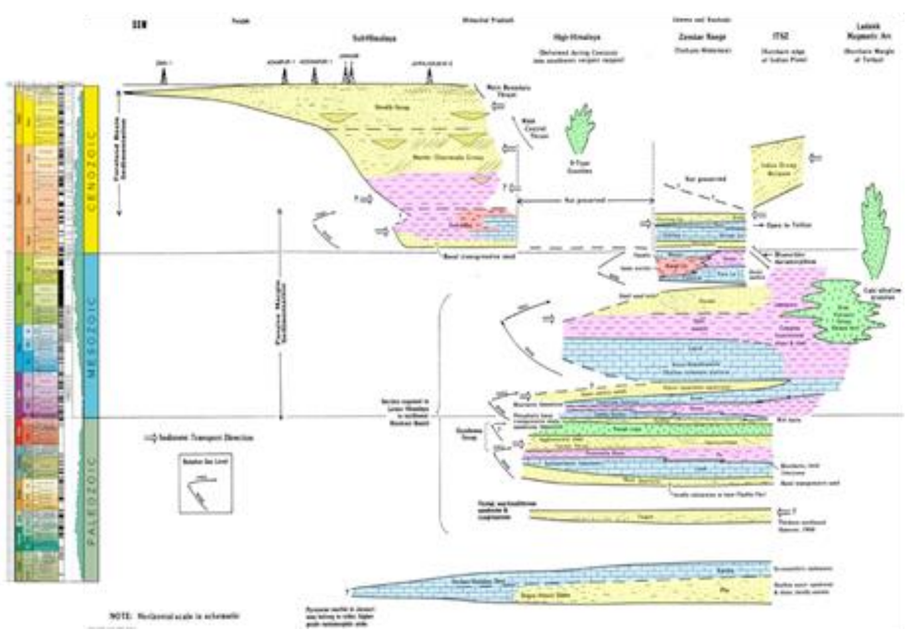

Figure 1. Phanerozoic (Palaeozoic, Mesozoic and Cenozoic) stratigraphy and petroleum systems in NW Himalaya

provide a direct date. Within the SLFm an important sedimentary marker horizon (black shale bed) was selected by Hakhoo et al. (2016) for the Re-Os geochronology. Their study yielded a Re-Os date of 607 ± 330 Ma, indicating that the Re-Os system was interrupted in response to hydrothermal fluid flow associated with the thrust tectonics in the region. Additionally, the decline of the total organic carbon (TOC) seems to have had an adverse effect on the Re–Os mobility and concentration. Since, the relative abundance of Re and Os is sufficient enough to attempt Re-Os geochronology of these shale samples. The analysis of the deep core samples should give reliable results and provide a dependable correlation tool to place the SLFm in context of the Peri-Gondwana margin successions with proven petroleum systems.

The Proterozoic Sirban Limestone Formation (SLFm) crops out as detached allochthons in the northwest Himalaya and has its coeval equivalents laterally disposed in the west in Salt Range, in the northwest in Abbotabad (Pakistan) and in southeast in Himachal Pradesh (India). The oil and gas occurrences have been reported from the Proterozoic successions globally and the hydrocarbon potential of the SLFm cannot be ruled out. The interbedded shales and algal laminated dolostones within the SLFm have yielded microflora comparable to those reported in the North African Neoproterozoic sandstones and the Late Proterozoic carbonates of the giant oil and gas fields of the Siberian Platform (Bhat et al., 2009). The SLFm contains a rich and diverse biota comprising ~ 10% of the rock volume in thin sections. The rich organic assemblage justified a hydrocarbon source potential analysis of the SLFm, tested in this study by Rock Eval (RE) Pyrolysis (Hakhoo et al., 2016). RE pyrolysis yielded a total organic carbon (TOC) content of 0.02 to 1 wt. % with very low Hydrogen Index (HI) values for the shales and TOC content averaging 0.02 wt. % for the dolostones. The organically lean shales and dolostones exhibit T_{max} values indicative of immature to post mature stage. But, since these values are for the samples with complex thermal and tectonic history, the results may be unreliable. The highly altered organic matter and kerogen present in the SLFm had the potential to generate hydrocarbons and presently indicates no significant source potential. This study is important for understanding the hydrocarbon occurrences in the SLFm particularly in the light of the recent oil and gas discoveries from the coeval Proterozoic successions elsewhere in the world.

The NW Himalayan region possesses suitable tectono-sedimentary environment, oil/gas shows and other elements of a petroleum system (Craig et al., 2018).

Although exploration efforts including the drilling of wells has considerably improved our understanding of the geological and structural setting and the hydrocarbon potential of the NW Himalaya, commercial discoveries have remained largely elusive. In the NW Himalaya the Precambrian-Cambrian sequences include the Salt Range Formation and also some sequences in the Lesser-and Sub-Himalaya include the Proterozoic SLFm; the Kashmir and Bhadarwah-Chamba basins further to the northeast, and the Garhwal Group and the Krol belt in the southeast. The Palaeozoic sedimentary rocks exposed within the Kashmir, Zanskar-Spiti, Kinnaur-Uttarakhand and Kumaon basins have been subjected to low grade metamorphism, and at present do not have any significant hydrocarbon generation potential. The Cambrian Khewra and the Permian Tobra formations form hydrocarbon bearing reservoirs in the East Potwar basin. The Palaeozoic stratigraphy of the Zanskar Tethyan Himalaya is rather similar to that of the Peshawar Basin. The thick argillaceous successions are the best potential hydrocarbon source rock horizons within the Palaeozoic. The Mesozoic and Early Eocene shallow marine successions of the Tethyan Himalaya are exposed in Kashmir, Zanskar, Chamba and Spiti basins. The Mesozoic successions include thick sequences of organic material rich argillaceous sediments. The Triassic and Jurassic strata are generally poorly developed or absent in the eastern Potwar basin, while they are thicker towards the west Potwar and Kohat basins. The sandstones of Jurassic age are proven reservoirs, and potential source rocks are present. The Kashmir basin is represented by limestone and shale formations of Triassic age. Some of the shales contain organic matter (OM) and could represent viable hydrocarbon source rocks, while some of the limestones, dolomites and sandstones have sufficient reservoir characteristics. The OM content of the argillaceous sediments within the Mesozoic-Tertiary succession of the Zanskar-Spiti basin is appropriate for hydrocarbon generation. The Sub-Himalaya Zone contains a sequence of Cenozoic sedimentary rocks divided into the Subathu and Dharamsala (=Murree) formations, and Siwalik Group. Hydrocarbon source rocks are present in the Subathu and Dharamsala formations; while the Lower Siwalik, Kasauli and Dagshai formations contain potential sandstone reservoirs. The Eocene Subathu Formation is a key exploration target in the NW Himalaya with both potential hydrocarbon source and reservoir rocks sealed by a thick clay sequence. The coeval shales within the Patala and Nammal formations are considered to be the main source rocks in the Potwar Basin, whereas, the fractured carbonates of Palaeocene and

Early Eocene age are the main reservoirs. The Miocene Murree Formation is the youngest oil-producing horizon in the Potwar basin. Palaeocene Hangu Sandstone and Lockhart Limestone are the main reservoirs in the Kohat basin. The stratigraphy of Kohat-Potwar basin extends into Margalla, Kalachitta and Samana Ranges. In these ranges the Jurassic-Eocene strata are exposed, so sub-thrust sheets could have hydrocarbon potential. In the NW Himalaya, the surface gas seeps are characterised by a high nitrogen content, and are either thermogenic or biogenic in origin, while the gases encountered in the wells are typically methane rich (dry) with low nitrogen concentrations, indicating thermogenic origin. There appears to be a strong linear correlation between the relative concentration of methane and nitrogen in the Himalayan fore-deep gas shows. There are numerous references to biogenic gas seeps in the Plio-Pleistocene sediments and lignite fields in the Kashmir Valley (Fig. 2), and also in the shallow Plio-Pleistocene sediments in the Peshawar Basin.

The evolution and establishment of the key petroleum system elements, the generation, expulsion, migration and accumulation (entrapment) of hydrocarbons at multiple stratigraphic levels in NW Himalaya has been controlled by the regional tectonic events. These events are associated with the source rock burial and maturation history, coupled with hydrocarbon generation, ‘peak oil’ and subsequent migration occurring concomitantly with the peak activity along the major regional thrusts. The complex and variable structural geometries have allowed a variety of traps beneath sections where source rocks have adequate burial depth, and where traps have not been breached. In NW Himalaya, the key to understand the direct relationship between tectonics and the evolution of petroleum systems are the accurate estimates for the timing of the related tectonics and that of the hydrocarbon generation, accumulation and critical moment. Here, the exploration has been hampered by the structural complexity, difficult terrain, drilling complications and

Figure 2. Biogenic gas being used for domestic consumption, Sadr-*e-Kot*, Kashmir Valley

poor seismic data quality. Timing of the trap formation *vs.* hydrocarbon charge, trap integrity, seal presence and capacity, and reservoir quality are the key geological risks that have to be addressed.

Record of the Permian Mass Extinction

The latest Permian mass extinction was the most severe in the past 540 million years and eliminated >90% of species in the ocean and ~70% of vertebrate families on land. The Guryul Ravine section (Kashmir, India) exposes the world’s most continuous and carbonated rock successions throughout the Permian-Triassic boundary and beyond. This section is unique in that it is the only ammonoid bearing expanded and complete Permian-Triassic boundary section along the entire southern Tethys margin. Although expanded ocean anoxia has long been believed to be a direct killing mechanism causing mortality of organisms during the Permian-Triassic mass extinction, little has been published on the extent and timing of this anoxia in Gondwana. The Guryul Ravine section in Kashmir, northern India, is a classic Permian–Triassic boundary (PTB) section containing high-quality marine sedimentary and fossil records, and thus provides a unique opportunity to study the redox conditions associated with the biotic crisis in the Gondwana region.

Huang et al (2019) generated high-resolution biotic and redox data from Kashmir to achieve an improved understanding of the nature of environmental stresses associated with the Earth's largest biocatastrophe. Their study, which evaluates pyrite framboid size and morphology reveals two pronounced stages of oceanic oxygen deficiency, in the assigned latest Permian Hindeodus *praeparvus*–Clarkina *meishanensis* Zone and the earliest Triassic Isarcicella *staeschei* Zone. Updated marine invertebrate fossil records show three sharp species richness declines at Guryul Ravine. The first decline occurred within uppermost Permian storm beds (Brookfield et al., 2013) and is interpreted to represent a facies control, in which a storm-agitated environment was inhospitable for benthos. The latter two biotic declines coincided with two marine anoxic events, as documented by pyrite framboid size distributions. The same two anoxic events are also recognized from PTB beds in the adjacent, relatively shallower Barus Spur section in Kashmir, in which newly obtained faunal data help to constrain placement of the PTB. Huang et al (2019) reported a new two-stage pattern of oceanic anoxia during the Permian–Triassic transition. They propose that the two anoxic events at Guryul Ravine correlate precisely with anoxic events in the Meishan GSSP and some sections in South China suggesting that this event sequence might have been characteristic of the Permian–

Triassic transition in some specific geological settings. The close relationship between oxygen depletion and species richness decline suggests that the former were an important contributor to the latter. In addition, they found that many framboids exhibit surface oxidation, reducing their overall size. However, the statistical analysis suggests that the mean oxidation-related reduction in size is<2.2%, thus having little effect on redox interpretations based on pyrite framboid sizes. The results demonstrate that, unlike many geochemical proxies, the pyrite framboid technique is still valid for redox interpretations of weathered samples.

Brosse et al. (2017) conducted new high resolution sampling, to assess the conodont biochronology and isotopic records of the fifteen lowermost stratigraphical metres (Member E) of the Khunamuh Formation at Guryul Ravine section (Fig 3). This interval includes both the Permian-Triassic and the Griesbachian-Dienerian (Induan) boundaries. The FO of *Hindeodus parvus*, the index for the base of the Triassic, is confirmed in the middle of sub-member E_2 (Unit 56 in Matsuda (1981); Brosse et al. (2017) bed GUR09). They calculated 10 Unitary Association zones based on the conodont record from China and from Guryul Ravine. UAZ_{1-2} are Late Permian and identified only in South China, UAZ_{3-10} are identified both in China and Guryul Ravine. The Griesbachian-Dienerian boundary is included within the interval of separation between UAZ_7 and UAZ_8. At Guryul Ravine, the boundary is precisely constrained between beds GUR310 and GUR311 and corresponds to the replacement of segminiplanate (here *Neogondolella*) to segminate (*Sweetospathodus* and *Neospathodus*) conodonts. Above this 40 cm uncertainty

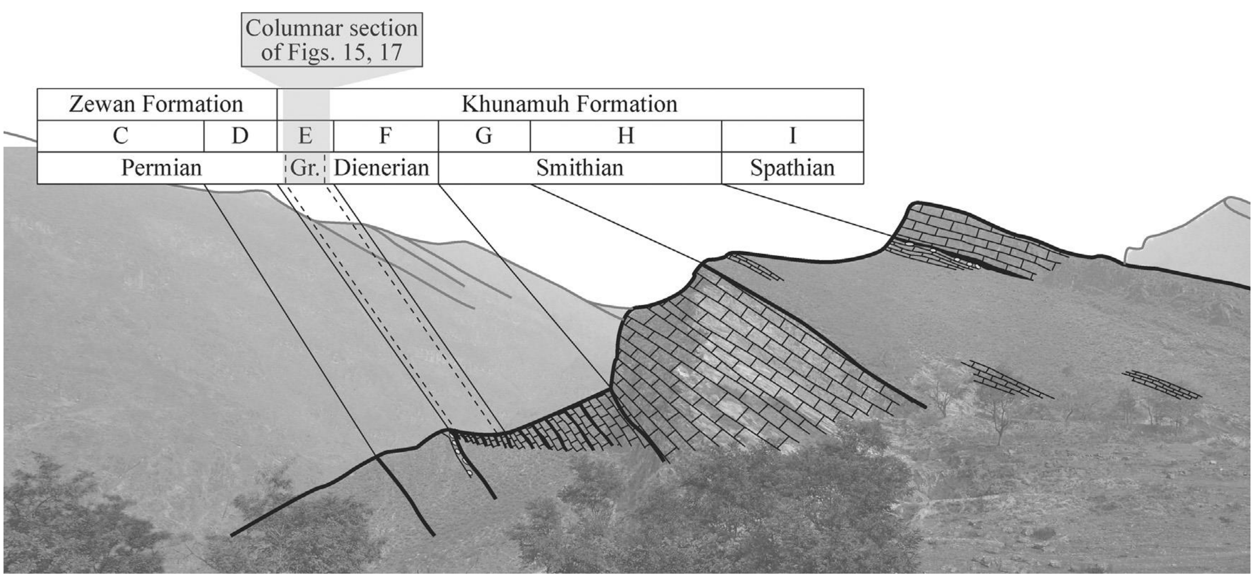

Fig. 3. The Guryul Ravine outcrop with the Members defined in Nakazawa et al. (1975)

interval, they also observe a conspicuous positive excursion of the $d^{13}C$ signal, which records a significant event at least at the scale of the Tethyan realm, and could be used as a secondary proxy for the Griesbachian-Dienerian boundary. This global perturbation of the carbon isotope signal is linked to a climate change at the Griesbachian-Dienerian transition, from a cool and dry to a hot and humid climate. This transition could be the trigger of the migration of neogondolellids towards the high latitude, and of the radiation of neospathodids during the Dienerian.

Recently during a field campaign, Krystyn et al. (2019) identified a fault within the Griesbachian part of the section. Although it can be detected in aerial photographs (if searched for) it is quite difficult to be seen in the field. As this structure has not been described in previous publications we assume that it has been overlooked and thus might account for some problems in stratigraphic correlation between previous studies.

Some previous studies debated that land vegetation collapse occurred before and followed by the marine extinction or to be asynchronous. Aftabuzzaman et al. (in preparation) analyzed normal-alkanes, pristine / phytane ratio, stable carbon isotopes, and organic carbon contents from shallow marine sedimentary rocks in multiple settings globally, including Liangfengya section and Meishan section in eastern part of Paleo Tethys and Bulla section at its western realms in low-latitudes as well as Guryul Ravine section at southern margin of Neo Tethys in high-latitudes, to clarify the timing and patterns of those biotic events. The analyzed results show that land vegetation collapses occurred twice before and after the marine extinction. Onset of first land vegetation collapse preceded the marine extinction at low-latitude sections in Paleo Tethys realms by 1 to 10 kyr., whilst the first collapse may have preceded ~4 kyr in northern hemisphere. Magnitude of land vegetation collapse in a high-latitude southern hemisphere section in northern India is lower than that in low-latitude northern hemisphere. The difference consists that the Siberian volcanism is a main cause of the mass extinction. The second land vegetation collapse occurred after the marine extinction in ~30 thousands of years. These land vegetation collapse coincided with the oceanic anoxia. They also show that the double land vegetation collapses could have caused the shallow-sea anoxia. Land vegetation recovery occurred after the marine extinction in 60 to 300 thousands of years.

Kumar et al. (2017) carried out petrography and, major and trace element geochemistry and, rare earth elements of the late Permian and early Triassic sediments of Guryul Ravine to examine the palaeoenvironmental conditions across the Permo-Triassic boundary. A visible change in the lithostratigraphy from argillaceous -carbonaceous mudstone in C Member of Zewan Formation, to fine grained argillaceous siltstone with quartz in D Member (4 m below the Late Permian Event Horizon) was observed. The XRD analysis divulges more terrigenous input below the PTB which is also reinforced by the dominance of quartz whereas, the dominant clay mineral is illite followed by chlorite. The $K_2O + Na_2O$ vs SiO_2 plot indicates that the sediments at PTB were derived from andesite type of rocks (SiO_2 52–63%) of intermediate composition. Major oxides SiO_2 , CaO, Na_2O and MnO are most abundant in the D Member, whereas E Member is enriched in the Co, Ni, Cu, V and Zn indicating reducing conditions. Dominance of incompatible elements such as Ti, K, Rb, and Sr in finer shale fraction shows increased reworking of sediments. Moderate weathering is observed at PTB, whereas, below the LPEH, physical weathering is more. Y/HO ratio varies from 24–51 indicating that REEs are derived from shale source. The C_{org} :P is < 10:1 in the late Permian whereas it is > 10:1 in the early Triassic Period suggesting that the conditions transformed from oxidizing to reducing (maximum values noticed in sample no.5 (80:1)) indicating suboxic-anoxic conditions, which may be one of the causes of oceanic redox at PTB.

Jasper et al. (2016) recorded the first palaeo-wildfire evidence in the form of charcoal documented in the Late Permian Zewan Formation at Guryul Ravine. This evidence is in the form of fragments of tracheids that show homogenized cell walls, a characteristic feature of charcoal. Considering that palaeo wild fire studies provide important palaeoecological information, their study is significant, as it allows reconstructing new information about environmental conditions during the deposition of the sediments of the Late Permian Zewan Formation.

Flora of Lower Carboniferous of Kashmir

Cleal et al. (2016) reported rich assemblage of mega flora from Lower Carboniferous section of Manigam (Anantnah Kashmir). This Sepukhovian fossil floras of the northern margins of Gondwana, on the shores of the Palaeotethys, are dominated by remains of an eligulate, mainly monopodial lycopsid with persistent leaves. The stems show considerable morphological variation that has historically resulted in the fossils having been assigned to many different fossil-species and -genera. However, there is now clear evidence that this simply reflects variation within a single fossil-species, for which the correct taxonomic name is *Spondylodendron pranabii*. Part of this morphological variation may have been due to variations in growth rate during the life of the individual plants, which in turn may reflect stressed growing conditions in a wetland habitat. The systematic position of *Spondylodendron* remains uncertain due to the lack of unequivocal evidence of reproductive structures, but it may have affinities with the Sublepidodendraceae.

Agnihotri et al. (2018) reported the first palynological data, supplemented by detrital zircon U–Pb ages, from the Fenestella Shale Formation of the Banihal near the Gund Village. This new floral assemblage provides new insights into the floristic evolution of Gondwana during the Late Palaeozoic, especially in India, from where the Carboniferous–Permian macro- and microfloral records are impoverished. They also for the first time attempted palynological correlation of the Carboniferous–Permian palynoassemblages from different Gondwana countries. The palynomorphs from the Fenestella Shale Formation are fairly well preserved and diversified and include 11 genera and 18 species. While the trilete spores and striate bisaccate pollen grains are scarce, monosaccate pollen taxa mainly – Parasaccites, Plicatipollenites and Potonieisporites are dominant. The assemblage is most similar to the Parasaccites korbaensis palynozone of the Lower Gondwana basins of the Indian peninsula and the Stage 2 palynozone of the late Carboniferous of east Australia. Besides, it is comparable with the known Carboniferous assemblages of Pakistan, Yemen and South America; Carboniferous-early Permian assemblages of South Africa and Permian assemblages of Antarctica. The sediment source of the siliciclastic shelf and delta deposits intercalated in the Fenestella Shale Formation is a hinterland in which Precambrian rocks dominantly were exposed and the Th–U ratios of detrital zircons suggest that most rocks exposed on the erosion level in the hinterland had a felsic composition. The youngest U–Pb zircon age of the investigated fossiliferous strata is 329 ± 16 Ma (late Visean to early Serpukhovian), providing a maximum age of deposition of the studied succession. Based on the affinities of the palynofloral assemblage and earlier palaeontological records, a warm, temperate and arid climate has been inferred for the Fenestella Shale Formation.

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