Hydrocarbon source rock potential evaluation of the Late Paleocene Patala Formation, Salt Range, Pakistan: Organic geochemical and palynofacies approach

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Organic geochemical and palynofacies analyses were carried out on shale intervals of the Late Paleocene Patala Formation at Nammal Gorge Section, western Salt Range, Pakistan. The total organic carbon content and Rock-Eval pyrolysis results indicated that the formation is dominated by type II and type III kerogens. Rock-Eval $T_{\max}$ vs. hydrogen index (HI) and thermal alteration index indicated that the analysed shale intervals present in the formation are thermally mature. S_1 and S_2 yields showed poor source rock potential for the formation. Three palynofacies assemblages including palynofacies-1, palynofacies-2 and palynofacies-3 were identified, which are prone to dry gas, wet gas and oil generation, respectively. The palynofacies assessment revealed the presence of oil/gas and gas prone type II and type III kerogens in the formation and their deposition on proximal shelf with suboxic to anoxic conditions. The kerogen macerals are dominated by vitrinite and amorphinite with minor inertinite and liptinite. The kerogen macerals are of both marine and terrestrial origin, deposited on a shallow shelf. Overall, the dark black carbonaceous shales present within the formation act as a source rock for hydrocarbons with poor-to-moderate source rock quality, while the grey shales act as a poor source rock for hydrocarbon generation.

Keywords. Patala Formation; Late Paleocene; TOC; palynofacies; Salt Range; Pakistan.

1. Introduction

The Potwar Basin (figure 1) is one of the most prolific petroliferous sedimentary basins in Pakistan which contains some of the formations which are important from hydrocarbon point of view, i.e., the Late Paleocene Patala Formation (e.g., Kadri 1995; Wandrey *et al.* 2004; Fazeelat *et al.* 2010; Zaidi *et al.* 2013). The Late Paleocene Patala Formation is dominated by carbonaceous

shale, limestone, sandstone and coal beds with subordinate marls in the Potwar Basin (Hanif *et al.* 2013; Sameeni *et al.* 2014). The carbonaceous shales and coal beds of the Patala Formation act as a potential source rock for many tertiary reservoirs in the Kohat Basin (Kadri 1995; Wandrey *et al.* 2004; Fazeelat *et al.* 2010) and hence the presence of carbonaceous shale and coal beds also appreciates hydrocarbon source rock assessment of Patala Formation in the Potwar Basin.

Figure 1. Tectonic map of the Potwar Basin, showing the location and tectonic setting of the studied section (i.e., black box). The inset map shows location of the study area with reference to Islamabad, Pakistan (after Jan *et al.* 2016).

The formation is well developed and exposed in the Salt Range, Kala-Chitta Range, Kohat and Hazara areas (Kadri 1995; Wandrey *et al.* 2004; Shah 2009). An appreciable earlier sedimentological, biostratigraphic and sequence stratigraphic research work is available on the formation in the context of its depositional environment, facies association, sequence stratigraphy, biostratigraphy and palaeontological character in the Potwar Basin (e.g., Wandrey *et al.* 2004; Sameeni *et al.* 2009; Hanif *et al.* 2013; Sameeni *et al.* 2014). However, no published research is available on its source rock potential evaluation at Nammal Gorge Section in the Salt Range, Potwar Basin. Thus, the proposed research paper is merely focused on hydrocarbon source rock potential evaluation of the Patala Formation.

Moreover, the fossil contents, sedimentary facies and depositional environment of a geologic formation are helpful in targeting a geologic formation for hydrocarbon source studies (Maravelis *et al.* 2013). In this regard, the work of Wandrey *et al.* (2004), Sameeni *et al.* (2009), Hanif *et al.* (2013) and Sameeni *et al.* (2014) were accessed to make the current elucidation more valid and acceptable. Sameeni *et al.* (2009, 2014) have carried out an

extensive work on biostratigraphy of the formation and identified age diagnostic larger foraminifer's species including *Nummulites mamillatus*, *Nummulites mammilla*, *Nummulites atacicus*, *Miscellanea miscella*, *Lockhartia haimeii* and *Alveolina veredenburgi* which are helpful in its age determination and global correlation. Likewise Hanif *et al.* (2013) identified a third-order high-stand system tract comprised of six vertically stacked parasequences indicating aggradation and three main microfacies including packstone, wacke-packstone and wackestone along with the intertidal open marine foraminiferal shoal to intertidal lagoonal environment for the formation. The elucidation of Hanif *et al.* (2013) indirectly gives an endowment for the current study as most of the source rock is reported from high-stand system tracts with suitable preservation of the organic matter (Emery and Myers 1996).

2. Geological settings

The northern margin of the Indian plate is occupied by an active fold and thrust belt of the Salt Range, formed in response to the collision

between the Indian and Eurasian plates (Baker *et al.* 1988). This ongoing collision between the Indian and Eurasian plates started some 55 million years ago as a consequence of northwards drift of the Indian plate (Yeats *et al.* 1984; Baker *et al.* 1988). The Salt Range Thrust (SRT) represents the southernmost thrust fault of Pakistan and also acts as the youngest compressional structure of the Himalayan orogeny (Grelaud *et al.* 2002). The study area lies in Salt Range (figure 1) and is considered to represent the frontal part of the tectonic wedge of Himalayan orogeny which passively translated northwards due to the basal decollement located in the Precambrian Salt Range Formation (Grelaud *et al.* 2002). The Salt Range forms the hanging wall, which had accommodated about 25–30 km shortening in the compressional regime of Himalayan orogeny (Baker *et al.* 1988). The Salt Range comprises of a series of anticlinal structures, being widest in its central part, between the Khewra and Warchha localities, while the folding becomes tighter, with the development of the faults as well in the southern part (Kazmi and Jan 1997). These anticlinal structures host productive petroleum accumulations in the southern part of the Potwar Basin (Grelaud *et al.* 2002). Eastwards, northeast trending ridges, Diljaba and Chambal-Jogi Tilla are formed by the bifurcation of the Salt Range structure due to the Jhelum Fault. Westwards, the Salt Range takes a narrow bend near Warchha and is separated from the Trans-Indus ranges by the strike-slip, Kalabagh Fault and southward, the range is truncated by the SRT (Gee 1989; Treloar *et al.* 1992). The Salt Range represents rocks ranging from Precambrian to Tertiary (figure 2) with intermittent unconformities (Gee 1989; Shah 2009; Iqbal *et al.* 2014). These rock units are distributed and exposed in the eastern, central and western parts of the Salt Range.

3. Methods and materials

The methodology adapted includes fieldwork and laboratory analyses.

3.1 Field investigation

A detailed geological field survey was conducted at the studied section (latitude 32°39'19"N and longitude 71°47'44"E) to sample and log the Paleocene Patala Formation (figure 3). Standard field methods of Tucker (2003) and Assaad (2008) have been

followed. A total of 15 outcrop samples were collected along the north face exposure to minimise the effects of weathering from direct sun light (Khan 2016). However, only seven representative rock samples were utilised for organic geochemical and palynofacies analyses. Field photographs of the diagnostic field features were taken to support the analytical interpretation (plate 1).

At the studied section, the Patala Formation is mainly comprised of carbonaceous shale, limestone and sandstone with minor marl and gypsum intercalations (figure 3). The shale is thin to medium bedded, carbonaceous, calcareous and laminated at places. The limestone is white to light grey in colour, nodular and occurs as interbeds with shale units. The sandstone is greenish to brownish in colour, fine to medium grained and thin to medium bedded. The formation has conformable contact with the underlying Middle Paleocene Lockhart Limestone and overlying Early Eocene Nammal Formation at Nammal Gorge Section (plate 1A and B). The total thickness of the formation at measured section is 70 m (figure 3), while maximum reported thickness is 182 m at Hazara area (Shah 2009).

3.2 Laboratory analyses (analytical procedures)

Bulk organic geochemical analyses including total organic carbon (TOC) and Rock-Eval pyrolysis were carried out on rock samples collected from the shale beds encountered within the formation at the studied section (figure 3). The organic geochemical analysis was performed at the laboratories of Hydrocarbon Development Institute of Pakistan (HDIP), Islamabad.

3.2.1 TOC analysis

TOC analysis involves heating of 300 mg pulverised rock sample at constant computer-programmed temperature in the helium inert environment, which gives TOC values in percentages. For TOC analysis of the representative rock samples (PN-1 to PN-14), TOC analyser, i.e., LECO-CS 300, was used in the laboratories of HDIP, Islamabad. Following the TOC analysis, rock samples having TOC values >0.5% were selected for further geochemical analysis (i.e., Rock-Eval pyrolysis).

3.2.2 Rock-Eval pyrolysis

The Rock-Eval pyrolysis is a standard screening technique used for evaluating the hydrocarbon

Figure 2. The generalised stratigraphic framework of the rocks exposed in the Salt Range and the Patala Formation is highlighted with light yellow colour; Fm: Formation, E: Early, M: Middle, L: Late, Quat; Quaternary, Pleis: Pleistocene (after Fatmi 1973; Shah 1977).

Figure 3. Lithologic log of the Patalla Formation, presenting the sample location, bed thickness and lithologic description of main lithologies at Nammal Gorge Section.

Plate 1. Displaying the representative field photos of the Patala Formation exposed at Nammal Gorge Section: (A, B) conformable contacts of the Patala Formation with underlying Paleocene Lockhart Limestone and overlying Eocene Nammal Formation at measured section, (C) carbonaceous shale (grey arrows) with pinched bed of light grey limestone (black arrow), and (D) grey shale having fissility, organic content (i.e., coal seams) and calcareous input.

potential of a source rock (Lafargue *et al.* 1998). It involves heating of ~100 mg crushed rock sample in pyrolysis oven having nitrogen atmosphere with a computer-controlled, temperature-programmed pyrolysis oven and oxidation oven (Behar *et al.* 2001). The main acquisition parameters measured during the Rock-Eval pyrolysis include S_1 (free hydrocarbon), S_2 (cracked hydrocarbon resulting from thermal cracking of kerogen) and S_3 (expulsion of oxygen-containing compounds) yields. The Rock-Eval also counts for the maximum temperature (i.e., T_{max} , °C) at which the maximum rate of generation of the S_2 peak occurs and can be used as a parameter to estimate the thermal maturity of organic matter (Hunt 1995; Hakimi *et al.* 2013). The Rock-Eval parameters including hydrogen index (HI), oxygen index (OI) and production index (PI) were also calculated as described by Peters and Cassa (1994) to evaluate the source rock potential (table 1). The representative rock samples were analysed using the Rock-Eval 6 in the laboratories of HDIP Islamabad, Pakistan.

3.2.3 Palynofacies analysis

The bulk organic matter of a sedimentary rock having both pollen and spores along with phytoclasts and amorphous organic matter (AOM), reflecting a specific depositional environment is referred as 'palynofacies' (Tyson 1995; Ercegovic and Kostić 2006; Traverse 2007). Rock samples were prepared and processed for palynological maceration using the standard preparation methods of Traverse (2007). Mineral acids including hydrochloric (HCl) (20%) and hydrofluoric (HF) (60%) acids were used to dissolve carbonates and silicates, respectively, from the rock samples. No oxidants/alkalis were used during the maceration process as such treatments can affect the natural colours of palynofacies components. The treated samples were neutralised and centrifuged in $ZnCl_2$ (having specific gravity of 1.9) to remove the heavy minerals. The organic residue was sieved through 20 μm nylon mesh and was mounted on glass slides using liquid Canada balsam. Two slides of each

sample were prepared from the organic residue. Nikon LV-100-ND fitted with DS-Fi2 Nikon digital camera was used for palynological counting and photo-microscopy. A total of 300 counts of palynofacies components per sample were made and their percentage proportions were calculated. The palynological processing was carried out in the Laboratory of Sedimentology and Palynology, National Centre of Excellence in Geology (NCEG), University of Peshawar.

4. Results and discussions

4.1 TOC results

The TOC values of the rock samples acquired from organic-rich shale intervals of the Patala Formation at Nammal Gorge Section are mostly >0.5% (table 1), in other words above the minimum limit required for a rock to act as a potential source rock (Hunt 1995; Makky *et al.* 2014; Selley and Sonnenberg 2014). Generally, the dark black carbonaceous shales (PN-5) of Patala Formation have moderate TOC values, while the dark grey shales (PN-14) have poor-to-moderate TOC values (table 1). More specifically, the TOC values of the shale intervals range from 0.54% to 0.90% with an average value of 0.67% (table 1), which suggests that the Patala Formation has poor-to-moderate TOC values and represents a rock with poor-to-moderate source rock quality at Nammal Gorge Section. Based on TOC results and their comparison with the published source rock standards (Peters 1986; Makky *et al.* 2014), it is assumed that the shale beds of the Patala Formation can act as a source rock for hydrocarbon generation with poor-to-moderate source rock quality. However, the TOC alone seldom evaluates a source rock sufficiently (Selley and Sonnenberg 2014; Khan 2016). Therefore, the Rock-Eval pyrolysis results need to be checked to

evaluate the source rock potential of the formation precisely.

4.2 Rock-Eval pyrolysis results

The Rock-Eval results of the analysed rock samples indicated that the S_1 yield of the Patala Formation ranges from 0.00 mg/g in the sample PN-1 to 0.02 mg/g in the sample PN-7 with an average value of 0.006 mg/g at the studied section (table 1). These values reveal that the small amount of the free hydrocarbons is present in the formation to act as a source for free hydrocarbons. More specifically, the S_1 values suggest that the Patala shales are poor source rocks for free hydrocarbons at the current outcrop setting (Peters 1986; Makky *et al.* 2014). Similarly, the S_2 yield (i.e., cracked hydrocarbons) ranges from 0.51 mg/g (PN-7) to 4.19 mg/g (PN-5) with an average value of 1.62 mg/g (table 1), which suggests that inadequate amount of hydrocarbons are present in the Patala carbonaceous shale beds, which can be released by thermal cracking of the kerogen. The S_2 yield of the representative rock samples depicts that the Patala Formation is a source rock for hydrocarbon with a poor-to-moderate source rock quality at the Nammal Gorge Section. The potential of the Patala Formation as a source rock needed further confirmation; thus before reaching a conclusion, we studied the Rock-Eval parameters including HI, PI, genetic potential, OI and thermal maturity ($T_{\max}$, °C) along with the source rock characteristics.

5. Source rock characteristics

The source rock characteristics used for the evaluation of the hydrocarbon potential of the Patala Formation are described in the following sections.

Table 1. TOC and Rock-Eval pyrolysis results of the representative rock samples of the Patala Formation.

Sl. no.	Sample code	TOC (wt%)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	GP (mg/g)	HI (mg/g)	OI (mg/g)	PI (mg/g)	$T_{\max}$ (°C)
1	PN-14	0.54	0.00	0.55	0.71	0.55	102	131	0.00	436
2	PN-11	0.65	0.00	0.54	1.01	0.54	85	155	0.00	447
3	PN-9	0.55	0.00	0.51	0.75	0.51	93	136	0.00	436
4	PN-7	0.71	0.02	1.72	0.86	1.74	242	121	0.01	441
5	PN-5	0.90	0.02	4.19	0.68	4.21	466	76	0.05	436
6	PN-3	0.61	0.00	0.60	0.71	0.60	98	116	0.00	447
7	PN-1	0.75	0.00	3.26	0.71	3.26	435	95	0.00	436
Average		0.67	0.006	1.62	0.78	1.63	217.28	118.6	0.009	439.9

Figure 4. Pyrolysis S_2 vs. TOC deciphering source rock generative potential and quality of the organic-rich intervals faced within the Patala Formation at studied section (after van Krevelen 1993; Hunt 1995; Hakimi and Abdullah 2014).

5.1 Source rock generative potential

It is the capability of a source rock to generate free hydrocarbons on thermal maturation (Hunt 1995; Hakimi *et al.* 2013). The source rock generative potential of the Patala Formation was evaluated using the TOC (wt%) vs. S_2 yield from the Rock-Eval pyrolysis and by comparing these values with van Krevelen (1993), Hunt (1995) and Hakimi and Abdullah (2014) published standards (figure 4). Generally, the TOC and pyrolysis S_2 yield values lie in the range of 1–100 (TOC wt%) and 0.1–1000 mg of HC/g for all organic lithologies in a sedimentary basin (Hakimi and Abdullah 2014; Selley and Sonnenberg 2014). However, in case of the Patala Formation, the S_2 values range from 0.51 to 4.19 mg of HC/mg at the studied section (table 1), which shows that the Patala Formation can generate the least amount of hydrocarbon (Maravelis *et al.* 2013; Makky *et al.* 2014). Thus, keeping in view the TOC and S_2 values of the rock samples and their comparison with the source rock standards, the source rock generative potential of the Patala Formation represents a rock with poor source rock potential (figure 4).

5.2 Kerogen types (*i.e.*, organic matter types)

Different types of kerogen can produce different types of hydrocarbons (Hunt 1995; Maravelis *et al.*

Figure 5. Plot pyrolysis S_2 vs. TOC content, deciphering kerogen types encountered within the Patala Formation (after Hunt 1995; Hakimi and Abdullah 2014).

2013; Hakimi and Abdullah 2014). The HI, TOC and S_2 yields were used to investigate kerogen types encountered within the Patala Formation (figure 5). The HI in the current study ranges from 85 mg HC/g (PN-11) to 466 mg HC/g (sample PN-5) with an average value of 217.2 mg HC/g, which corresponds to different types of kerogen within the formation after plotting these values in bivariate standard kerogen plots (table 1; figure 5). Kerogen classification diagrams were constructed following van Krevelen (1993), Mustapha and Abdullah (2013), Hakimi and Abdullah (2014) and

Figure 6. HI vs. pyrolysis $T_{\max}$, showing kerogen types, quality and thermal maturity stages of the organic-rich intervals of the Patala Formation (after van Krevelen 1993; Hakimi and Abdullah 2014).

Makky *et al.* (2014) as shown in figure 6. These classification diagrams indicated that the Patala Formation is dominated by type II and type III kerogens. The type II kerogen is prone to both oil and gas generation on the achievement of optimum thermal maturity while type III kerogen is prone to only gas generation (Mustapha and Abdullah 2013; Hakimi *et al.* 2014).

5.3 Thermal maturity level

The achievement of optimum thermal maturity of organic matter is essential for a rock to act as a prolific potential source rock as immature or post-mature source rocks cannot generate hydrocarbons (Makky *et al.* 2014; Mashhadi *et al.* 2015). The thermal maturity is estimated using $T_{\max}$ and HI

from the Rock-Eval data. In case of the Patala Formation, the $T_{\max}$ values range from 436° (PN-1) to 447°C (PN-11) with an average value of 439.9 (table 1), which indicates that the organic-rich intervals of the formation are thermally mature and can generate hydrocarbons if rest of the source rock prerequisites are available (figure 6). In a sedimentary basin, both the burial depth and organic matter type affect the thermal maturity levels of organic matter (Selley and Sonnenberg 2014; Mashhadi *et al.* 2015). Here, in case of the Patala Formation, the change in thermal maturity levels is also due to change in burial depth as well as due to change in types of the organic matter (table 1; figures 3 and 6). $T_{\max}$ vs. HI plot deciphered that the organic-rich intervals present within the Patala Formation are thermally mature and can generate hydrocarbons (figure 6).

6. Palynofacies characterisation

Source rock investigators have used various terms for palynological matter including sedimentary organic matter, organic matter, palynodebris, palynomaceral and kerogen macerals (Lorente 1990; Tyson 1995; Pittet and Gorin 1997; Traverse 2007). The current study uses the terms palynofacies and kerogen macerals for sedimentary organic matter faced within the formation (tables 2 and 3). Palynofacies components are classified into phytoclasts, palynomorphs and AOM for quantitative analysis of kerogen encountered within the formation (table 2).

6.1 Phytoclasts

The term phytoclast was first introduced by Bostick (1971) and includes all structured organic

components of kerogen that vary in size from clay to fine sand-sized particles excluding palynomorphs (Zobaa *et al.* 2013). Opaque phytoclasts/inertinite encountered within the formation are responsible for dry gas generation and are included in type III kerogen macerals (plate 2, figure 1) while translucent phytoclasts/vitrinite are responsible for wet gas generation on the achievement of optimum thermal maturity and are included in type II kerogen macerals (plate 2, figures 2 and 3; Tyson 1995; Al-Belushi 2006; Ercegovic and Kostić 2006; Mirzaloo and Ghasemi-Nejad 2012; Zhang *et al.* 2015).

6.2 Palynomorphs

The term palynomorph was introduced by Tschudy (1961) to describe all the distinct organic-walled, HCl- and HF-resistant microfossils collected in

Table 2. *Palynofacies components and their percentage distribution present within the Patala Formation at Nammal Gorge Section.*

Palynofacies	Sample code	Palynomorphs (%)	Phytoclasts (%)	AOM (%)
Palynofacies-3	PN-14	0	40	60
	PN-11	0	42	58
Average		0	41	59
Palynofacies-2	PN-9	1	42	57
	PN-7	1	44	55
Average		1	43	56
Palynofacies-1	PN-5	0	44	56
	PN-3	1	47	52
	PN-1	2	48	50
Average		1	46.33	52.67

Table 3. *Kerogen macerals and their percentage abundance encountered within the Patala Formation at studied section.*

Palynofacies	Sample code	Inertinite (%)	Vitrinite+cutinite (%)	Amorphinite+liptinite (%)
Palynofacies-3	PN-14	10	38	52
	PN-11	12	38	50
Average		11	38	51
Palynofacies-2	PN-9	18	45	37
	PN-7	20	44	36
Average		19	44.5	36.5
Palynofacies-1	PN-5	22	46	32
	PN-3	24	45	31
	PN-1	25	45	30
Average		23.67	45.33	31

Plate 2. Palynofacies components including phytoclasts, foraminiferal linings, palynomorphs and AOM present within the Patala Formation at studied section: (1) opaque phytoclast/inertinite thermally inert or can only generate dry gas; (2) translucent phytoclasts/vitrinite prone to dry gas and wet gas generation; (3) biostructured phytoclasts with original rectangular and triangular cellular structures derived from terrestrial plants; (4) and (5) foraminifer's linings that can act as diagnostic fauna of the Paleocene Epoch; (6) lipid-rich palynomorphs that can generate liquid hydrocarbon on achieving of thermal maturation; (7–9) granular AOM, thermally cooked AOM and jellified AOM, respectively, which are responsible for oil generation.

maceration processes (plate 2, figures 4–6; Traverse 2007; Zobaa *et al.* 2013). The palynomorphs/liptinite encountered are prone to liquid

hydrocarbon generation and are included in type I kerogen macerals (plate 2, figure 6; Zobaa *et al.* 2013; Singh and Mahesh 2015; Zhang *et al.* 2015).

Plate 3. Dry gas prone palynofacies-1 having type III kerogen encountered within Patala Formation at Nammal Gorge Section: **(A)** foraminiferal linings (yellow arrows), inert or only dry gas prone inertinite/opaque phytoclasts (black arrows), oil prone granular AOM (grey arrows); **(B)** inert inertinite/opaque phytoclasts (black arrows), vitrinite/brown phytoclasts (pink arrows), oil prone AOM (grey arrows); **(C)** inertinite (black arrows), biostructured phytoclast (pink arrow), jellified AOM (grey arrows); and **(D)** gas prone vitrinite (pink arrows), oil prone amorphinite (grey arrows).

These beds comprise dark black shales and though sparsely placed, these lithologies bear striking similarities. Palynofacies-1 kerogen macerals include 23.67% inertinite, 45.33% vitrinite, 31% AOM/amorphinite along with the minor amount of lipinites (plate 3, figures A–D). The inertinite and vitrinite are well preserved and are elongated to lath shaped and reveal moderate transportation from the source area (plate 3, figures A and B). The inertinite and vitrinite are well structured and showed sharp outlines in transmitted light suggesting good preservation and suitability for hydrocarbon generation (Traverse 2007; Filho *et al.* 2012). The lipinites macerals include few biodegraded spores and some foraminifer's linings, which deciphers poor preservation of palynomorphs in the formation (plate 3, figure A). The AOM is light brown to dark brown and is granular in nature with diffuse outlines and nicely preserved in the formation which possesses suitability for liquid hydrocarbon generation (Zobaa *et al.* 2013). Based on the percentage distribution of kerogen macerals while

following Dow (1982) liptinite–vitrinite–inertinite (LVI) ternary kerogen plots, this palynofacies lies in the dry gas zone for which type III kerogen has been suggested (figures 7 and 8). While plotted on Tyson (1995) AOM–phytoclast–palynomorphs (APP) ternary kerogen plot, this palynofacies occupied proximal suboxic–anoxic shelf environment (figure 9) for which Tyson (1995) has interpreted the presence of type III and type IV kerogen. In palynofacies-1, vitrinite is dominant which is prone to dry gas generation on optimum thermal maturity. The presence of inertinite suggests an inert and barren type IV kerogen, while the presence of amorphinite suggests oil prone type I kerogen for this palynofacies; however, their lower concentrations seldom do so as the palynofacies is mainly dominated by vitrinite macerals (table 3). Thus, palynofacies-1 represents the dry gas prone type III kerogen at Nammal Gorge Section. This palynofacies also possesses moderate TOC and Rock-Eval results (table 1) and hence proved that it can act as a moderate source rock for hydrocarbon.

7.2 Palynofacies-2

Palynofacies-2 is identified and faced within samples PN-7 and PN-9 collected from the middle part of the formation (figure 3). This palynofacies encompassed 19% inertinite, 44.5% vitrinite and 36.5% AOM/amorphinite and lip-tinite/palynomorphs (plate 4, figures A–D). The vitrinite and inertinite of palynofacies-2 are well preserved and elongated to equidimensional in shape which reflects more transportation from the source area compared to palynofacies-1. The vitrinite (i.e., brown/translucent phytoclasts) are responsible for dry gas generation and amorphinite are responsible for the liquid hydrocarbon generation (provided optimum thermal maturity; Ding *et al.* 2013). Based on the quantitative analysis, this palynofacies is dominated by vitrinite and amorphinite with minor liptinite and thus occupies a wet gas and condensate prone zone on LVI ternary kerogen plot of Dow (1982) for which Tyson (1995) has suggested type II kerogen (figures 7–9). The presence of vitrinite macerals

is responsible for dry gas generation, while amorphinite and liptinite macerals are responsible for oil generation, thus the overall type II kerogen is suggested for this palynofacies. Based on the quantitative analysis of palynofacies components, palynofacies-1 represents the proximal suboxic–anoxic shelf setting on Tyson (1995) ternary APP kerogen plot (figure 9) for which Tyson (1995) has interpreted type II kerogen which supports the current assumption (i.e., the presence of type II kerogen) (plate 5).

7.3 Palynofacies-3

Palynofacies-3 is encountered and identified within samples PN-11 and PN-14 acquired from the upper part of the formation (figure 3) though the beds are sparsely placed, but possesses striking similarities from palynofacies point of view. The kerogen macerals encountered within this palynofacies resulted in 11% inertinite, 38% vitrinite and 51% AOM/amorphinite. The AOM is yellowish to light brown in transmitted light with

Plate 4. Wet gas and condensate prone palynofacies-2 encountered within the formation and possess relatively more AOM compared to palynofacies-1: (A) palynomorph (yellow arrow), inertinite/opaque phytoclast (black arrow), vitrinite/brown phytoclasts (pink arrows) AOM (grey arrows); (B) opaque phytoclasts (black arrows) and jellified oil prone AOM (grey arrows); (C) dry gas prone vitrinite (pink arrows), palynomorph oil prone (yellow arrow), jellified AOM (grey arrow); and (D) foraminiferal lining abundant fauna of Early Tertiary period (pink arrow), black/opaque phytoclasts (black arrows).

Plate 5. Palynofacies-3 having oil and gas prone type II kerogen encountered within the Patala Formation at Nammal Gorge Section: **(A)** gas prone vitrinite/brown phytoclasts (pink arrows) with some oil prone AOM/amorphinite; **(B)** dry gas prone brown phytoclasts/vitrinite (pink arrows) and oil prone jellified AOM (grey arrows); **(C)** oil prone amorphinite/AOM (grey arrows); and **(D)** dry gas prone vitrinite (pink arrows), oil prone amorphinite/AOM (grey arrows).

no sharp out lines, jellified as well as granular in nature and is prone to liquid hydrocarbon generation (Traverse 2007). This palynofacies lack palynomorphs which suggests more transportation towards the basin compared to palynofacies-1 and -2. Based on kerogen components percentages and their distribution on ternary kerogen plot of Dow (1982), type II kerogen is established for this palynofacies, which is prone to both oil and gas generation on optimum thermal maturity (figures 7 and 8). On Tyson (1995) ternary APP kerogen plot, the palynofacies-3 occupies proximal suboxic–anoxic shelf setting (figure 9) which also appreciated type II kerogen.

8. Thermal maturity

Palynomorphs show colour variation as a function of thermal maturity and with increase in temperature the colour of palynomorphs changes from pale yellow to orange brown and brown to black, while this change is progressive, cumulative

and irreversible in nature (e.g., Pross *et al.* 2007; Jiang *et al.* 2008; Filho *et al.* 2012). Thermal alteration index (TAI) and spore colour index (SCI) are maturation indicators that measure the colour of palynomorphs for the estimation of thermal maturity instead of vitrinite reflectance (Pross *et al.* 2007; Jiang *et al.* 2008; Ding *et al.* 2013). An attempt was made to elucidate the thermal maturity of the kerogen while noticing the variation in spore colouration, but palynomorphs species indicative of variation in colours (i.e., *Deltiodospora* sp., *Classopollis torosus* sp.) were not found within the formation. However, phytoclasts and AOM were used for comparison with the standard colour charts. The thermal maturity ranges from 0.6 to 1.8 on SCI and TAI which suggests that the organic-rich intervals of the formation are thermally mature and can generate hydrocarbons. The phytoclasts colour changes from golden yellow to dark brown, while AOM colour changes from pale yellow to orange brown which deciphered that the thermal maturity increases from top to bottom and

this interpretation also agreed on the geochemical interpretation (table 1; figure 6).

9. Conclusions

The conclusions drawn as a result of the current study are summarised as follows.

The TOC, Rock-Eval pyrolysis and palynofacies data indicated that the Patala Formation is dominated by type II and type III kerogens at Nammal Gorge Section.

The $T_{\max}$ and HI values revealed that the organic matter present within the formation is thermally mature and can generate hydrocarbons. The variation in the thermal maturity of organic matter is due to change in burial depth as well as due to change in the type of the organic matter.

The organic geochemical results showed that the dark black carbonaceous shale intervals of the formation contain sufficient amount of organic matter (i.e., 0.90 wt% TOC) to act as a moderate source rock, while the grey shale intervals can act as a poor source rock for hydrocarbon generation in the western Salt Range.

Three palynofacies assemblages including palynofacies-1, palynofacies-2 and palynofacies-3 are identified within the formation, which are prone to dry gas, wet gas and oil generation, respectively.

Palynomorphs encompassed within the formation include mostly foraminiferal linings and hence appreciate Late Paleocene Age for the formation.

The palynofacies analysis indicated that the kerogen face is dominated by vitrinite, amorphinite and inertinite, respectively, with minor liptinite macerals and macerals are of both marine and terrestrial origin, deposited on a shallow shelf environment.

Integrated geochemical and palynofacies investigations deciphered that the black carbonaceous shales are moderate source rocks for hydrocarbon, while the grey shales are poor source rock at the Nammal Gorge Section, western Salt Range.

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