Sedimentary organic matter as a proficient tool for the palaeoenvironmental and palaeodepositional settings on Gondwana coal deposits

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Received: 19 August 2021 / Accepted: 12 October 2021 / Published online: 22 October 2021
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Abstract

Palynofacies is based on the different types of the dispersed/sedimentary organic matter (DOM/SOM) and has been used as a proficient proxy for the palaeoclimatic reconstructions in sedimentary deposits of various time spans. It has also been acknowledged as an effective tool in the different domains like sequence biostratigraphy, palyno-biostratigraphy, palaeodepositional history, identification for depositional processes, oxic–anoxic environment, and variations in the water depth. It has been emerged as an analytical tool in palaeoclimatic reconstruction, which could complement geophysical and geochemical datasets. Since long palynofacies analysis has been exclusively applied in the marine sediments, it has recently dragged the attention of many researchers as a significant parameter for palaeoclimatic interpretation in continental deposits. In the last few decades, more consideration was focused on palynofacies that have become an essential proxy in the biostratigraphic and other non-biostratigraphic fields due to its requirement in the petroleum industries. The present study provides a basic idea of dispersed organic matter characterization, methodology, interpretations, and its application with special emphasis on the Gondwana deposits. The study also includes the summary of the worldwide distribution of the Gondwana sediments, especially for palaeodepositional settings through palynofacies along with other parameters.

Keywords Palynofacies · Gondwana · Palaeoenvironmental reconstructions · Palaeodepositional settings

Introduction

Combaz (1964) coined the term palynofacies and was described by Powell et al. (1990). Since long, palynofacies analysis has been extensively applied in the various sediments of different periods by various workers (Singh et al. 1992; Traverse 1994; Graz et al. 2010; Garcia et al. 2011; Aggarwal et al. 2019a, b, c) for the source rock potential by using the transmitted light microscopy, as illustrated by Tyson (1995). Previously, the palynofacies analysis was only confined to the marine settings solely for the petroleum sectors. It has not only played a substantial role in the palaeoenvironmental settings in the marine succession (Götz et al. 2003; Oboh-lkuenobe et al. 2005; Hermann et al. 2012; Carvalho et al. 2013; El Atfy et al. 2014) but also has

been applied on the continental successions of different sedimentary horizons, including coal/lignite (Singh et al. 1992; Closas et al. 2005; Cazzulo-Klepzig et al. 2009; Wheeler and Götz 2016, 2017; Cornamusini et al. 2017; Götz et al. 2017; Aggarwal et al. 2019a, b, c). The palynofacies study has now been expanded in various types of lacustrine (Aggarwal et al. 2019b) and fluvial systems delineating its importance to coal deposits (Aggarwal et al. 2019a, b, c), understanding the processes and factors responsible for the sediment deposition.

In palynofacies investigation, the total organic matter in the sediments is scrutinized, which decreases the taphonomical preconceptions to a great level and permits interpreting source rock provenance for applied scientific aspects. It has recently been incorporated in the basin analysis, producing geological models to represent the direct quantification and qualifications of the different types of organic matter in a specific sediment/rock. This is found to be helpful in designing the geological models, especially in the sedimentary carbonate systems, due to various chemical, geological, physical, and biological parameters that govern deposition

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in these environments. This proxy is also helpful in providing information about the provenance of the organic matter sedimentary and palaeobiological dynamics and gives an idea about the gas and oil generation potential.

Palynofacies analysis has also been acknowledged as an efficient tool in domains like sequence biostratigraphy, palyno-biostratigraphy, proximal–distal trends, identification for depositional processes, oxic–anoxic environment, and variations in the water depth (Zobaa et al. 2011; Mueller et al. 2014; Tyson and Follows 2000). It is being used as an analytical proxy in palaeoclimatic reconstruction, which could complement the combination of geophysical and geochemical datasets (Mueller et al. 2014; Zhang et al. 2015). Palynofloral record, along with palynofacies, has become a reliable tool for enhancing the accuracy and consistency of

palaeoclimatic reconstructions based on palaeophytogeography, palaeoecology, and palaeoclimatology (Modie 2007; Césari and Colombi 2016; Lindström et al. 2016).

Previous studies have signified the application of palynological, palynofacies, and sedimentological investigations to demarcate the biostratigraphy and palaeodepositional settings in the sediments of different ages (Götz et al. 2003; Cazzulo et al. 2009; Hermann et al. 2012). Integrated approaches of biostratigraphy and palynofacies are widespread and used to be widely applied for the regional Gondwana sediments of both marine and continental settings (Martinez et al. 2008; Zavattieri et al. 2008; Guler et al. 2013; Zobaa et al. 2013; Gonçalves et al. 2015; Zhang et al. 2015; Aggarwal et al. 2015, 2017, 2019a; b, c; Murthy et al. 2019) in various continents. Map (Fig. 1) shows the different

Fig. 1 Locations of palynofacies studies carried out in various Gondwana deposits. 1. India: Tripathi 1997 (Mahanadi Basin); Ram-Awatar et al. 2005 (South Rewa Basin); Aggarwal et al. 2015, 2017, 2019a,b, c; Mishra et al. 2018; Mishra and Singh, 2018 (Godavari Valley Coalfield); Murthy et al. 2019 (Wardha Coalfield); Murthy et al. 2020 (Damodar basin); Kumar et al. 2021 (Jaisalmer Basin). 2. Pakistan: Hermann et al. 2012 (Salt Range). 3. Sri Lanka: Weera-koon et al. 2019 (Tabbowa Basin). 4. Antarctica: Kumar et al. 2011 (Allan Hills); Cornamusini et al. 2017 (Northern Victoria Land). 5. Australia: Wetering et al. 2013 (Bowen Basin); Wheeler et al. 2019 (Galilee Basin). 6. Argentina: Césari and Colombi, 2016 (Ischigualasto-Villa Unión Basin); Marcelo et al. 2008; Martinez et al. 2008; Zavattieri et al. 2008; Guler et al. 2013; (Neuquén Basin); Olivera et al. 2015 (Cañadón Asfalto Basin); Quattrocchio et al. 2006 (Tierra del Fuego). 7. Brazil: Carvalho et al. 2006 (Northeastern Brazil); Cazzulo et al. 2005 (Parana basin Brazil); Cazzulo et al. 2009 (Faxinal Coalfield). 8. Africa: Modie 2007; Götz and Ruckwied

2014; Wheeler and Gotz 2016; Ruckwied and Götz 2016 (Karoo Basin); Wheeler and Gotz 2017 (Witbank Coalfield); Götz et al. 2020 (Moatize sub-basin); Ruckwied et al. 2014 (Permian Ecce Group); Peters et al. 2013, 2015 (West Africa); Zobaa et al. 2011, 2013 (Egypt). 9. US: Tyson 1984 (Blake-Bahama Basin, western Central Atlantic). 10. Denmark: Buchardt and Nielsen 1991 (Gassum Formation); Dybkjær 1991; Batten et al. 1994 (Danish basin). 11. Portugal: Gonçalves et al. 2015 (Lusitanian Basin); Paula Alexandra Sá da Silva Gonçalves 2014. 12. France: Steffen and Gorin 1993; Courtinat 2003. 13. Germany: Ruf et al. 2005; Müller et al. 2006 (Saar–Nahe Basin); Christoph et al. 2019. 14. Poland: Fijalkowska 1995; Pieńkowski and Waksmundzk 2009; Gedl and Ziája 2012. 15. Sweden: Lindström and Erlström 2011. 16. Norway: Van der Zwan, 1990; Mueller et al. 2014. 17. Hungary: Götz et al. 2003; Götz et al. 2009. 18. UK: Tyson 1989; Slater and Wellman 2015. 19. Russia: Grigoriev and Utting 1998. 20. China: Zhang et al. 2010, 2015 (Ordos Basin). 21. Iran: Zarei 2017

locations where palynofacies studies have been carried out worldwide in Gondwana deposits.

Palynofacies analysis

The accumulation of various forms of the organic matter components (pollen grains, spores, plant tissues, tracheids, resins, filaments, fungi, algae, acritarchs, foraminiferal test linings, etc.) depends upon the different processes like sedimentary, physical, and biochemical (Aggarwal et al. 2019a, b, c). After decay, demise, and burial, diverse plant communities represent different types of taphonomical and preservational characters demonstrating the setting of their transportation and primary procedures (autochthonous and allochthonous) in the dispersed organic matter.

Palynomorphs (percentage of total kerogen)

Palynomorphs include sporomorphs, phytoplankton, and zoomorphs. Their specific organization defines the appearance of palynomorphs in the sedimentary organic matter at the cellular level. A high proportion of continental palynoflora (Cordiates, Glossopterids, conifers, lycopsids, sphenopsids, filicopsids, etc.) indicates proximity to terrestrial sources (Tyson 1995), while the presence of the marine palynomorphs (dinoflagellate cysts, foraminiferal test linings, scolecodonts, prasinophytes, etc.) indicates the proximity of the source towards the marine regime.

Structured organic matter (percentage of total kerogen)

The predominant occurrence of phytoclasts is mainly related to the oxic conditions (Mendonça Filho et al. 2010). The structured phytoclast specifically includes brown translucent woody fragments (poorly/well preserved) with tracheids (uni- or biserial arrangement of rows of pits), vessels, and elongated elements (Batten 1996), tubes and filaments, plant tissues. One more category that lies under this class is planar organic remnants (cellular or non-cellular). Cellular structures are mainly associated with the yellowish brown, thin, unevenly folded, transparent or translucent cuticles (Batten 1996). Recently a new category has also been included in it called gelified phytoclasts (Zhang et al. 2015). The principal prevailing reason of phytoclasts allocation is the distance travelled over which particles have been transported (Carvalho et al. 2013). The large-sized phytoclast particles are deposited near the sources, which are considered as the proximal. In contrast, the small-sized phytoclasts are deposited in the distal part like in deep waters by turbidity currents (Habib 1982).

Opaque black woody tissues (percentage of total kerogen)

The opaque particles/charcoal (OP) is formed of wood particles in highly oxidizing conditions that range from black to dark brown under transmitted light. Black opaque phytoclasts are produced due to the oxidation of the translucent organic matter transported over a prolonged period at a normal or elevated temperature (Ercegovic and Kostić 2006).

Degraded organic matter (percentage of total kerogen)

The biodegraded organic matter is produced due to fungal and bacterial activities on the structured organic matter. A fungus is one of the most viable degrading agents which convert plant fragments into diverse organic matter types with the help of biological processes. The influx of fungi on the organic matter stimulates bacterial degradation in the later stages. Amorphous organic matter is derived from phytoplankton or by the action of fungi/bacteria on partially degraded organic matter that converts them into a structureless amorphous mass. Such amorphous matter looks to be porous and spongy (ranging from partial to complete degradation).

Methodology

Palynofacies involve the classification of diverse types of the dispersed organic matter remains (like brown/opaque phytoclasts, palynomorphs and light/dark AOM matters), size, and state of preservation. Identification of the palynofacies is chiefly established by Batten (1996), Tyson (1989, 1993, 1995), and later various other authors (Tschudy 1969; Minshall et al. 1985; Bustin 1988; Van Bergen et al. 1990; Williams 1992; Wood and Gorin 1998; Mishra et al. 2018; Aggarwal et al. 2017, 2019a; b, c) have enhanced the criteria of the identification.

For the processing of the samples of palynofacies analysis, a standard non-oxidative procedure is usually followed (Faegri and Iversen 1989; Tyson 1995; Batten 1999; Prasad et al. 2013). About 10–20 gm of the material from each sample was taken and crushed into small-sized pieces (not powder) with the help of a pestle and mortar. First, treated with hydrochloric acid (HCl) and followed by hydrofluoric acid (HF) to remove the carbonate and silicates in the sediments, respectively. The material is thoroughly is washed and sieved 37 µm (400 mesh)/25 µm (500 mesh) size, and later on, the material was spread and dried on a coverslip with the help of the polyvinyl alcohol (PVA). Finally, the dried coverslip is mounted using Canada balsam, and permanent slides are prepared. Three to four permanent slides

from each sample are observed with the help of a microscope with a transmitted light mode. As a minimum, 500 organic particles are counted from each sample at variable magnifications to attain statistically significant organic matter content and diversity (quantitative and qualitative data) for the study. The palynofacies parameters were computed to calculate relative abundances. For identifying numerous palynofacies zones/assemblages in the studied succession, any statistical software that may be used like CONISS can be performed with the help of TILIA ver 1.7 (Grimm 1987, 1990; Hammer et al. 2001).

Characterization of palynofacies

The different authors have proposed various classification systems for the palynofacies analysis (Lorente and Van Bergen 1991; Tyson 1995; Batten 1996; Mendonça Filho et al. 2002; Oboh-Ikuenobe and Villers 2003; Carvalho et al. 2006; Ercegovic and Kostić 2006; Zhang et al. 2015; Aggarwal et al. 2019a, b, c). Detailed classification for the sedimentary organic matter is summarized in Table 1. The palynofacies are mainly classified into four major groups: (1) palynomorphs, (2) structured phytoclast, (3) opaque phytoclast, and (4) degraded organic matter.

Palynomorphs

Palynomorphs in the sedimentary organic matter (Fig. 2a–b) are recognized by their specific cellular structure, shape, and morphology. This group is divided into three subgroups which include (a) sporomorphs, (b) phytoplankton, and (c) zoomorphs.

Sporomorphs include two categories spores and pollen grains. Continental spores include triletes, monoletes, alete spores, and fungal spores. These spores (Fig. 2c–d) may be pteridophytic (lycopsids, sphenopsids, filiciopsids), bryophytic, and fungal (Fig. 2e–f) in origin. Pollen grains include monosaccates (Fig. 2g), non-striate bisaccates (Fig. 2h), striate bisaccates (Fig. 2i–j), taeniates (Fig. 2k–l), monolete (Fig. 2m), aletes (Fig. 2n). These pollen grains are produced by gymnosperms (Cordaitea, Glossopterids, conifers, Cycads, Voltzalean, and Peltasperms). These categories are exclusively continental in origin.

Phytoplanktons are further subdivided into three categories: Chlorococcale algae, Dinoflagellate cysts, and Prasinophytes (illustration: Mays et al. 2021). Chlorococcale algae (illustration: plate 7, Fig. 6–9; Mendonça Filho et al. 2011) are exclusively colonial algae (*Botryococcus* and *Pediastrum*). Dinoflagellate cysts (Fig. 3a) are produced during the sexual part of the life cycle of

Class Dinophyceae survives. Prasinophytes are defined as fossilizing structures produced by tiny quadriflagellate algae (Division Pyrrhophyta). Most, like Tasmanites, are spherical; diameter 50–2000 µm, smooth and thick-walled. Dinoflagellates and Prasinophytes are marine in origin.

Zoomorphs are further divided into categories, viz. Acritarchs (illustration: plate 7, Fig. 18–19; Mendonça Filho et al. 2011), Foraminiferal test linings (Fig. 3b), and Scolecodonts (illustration: plate 8, Fig. 3; Mendonça Filho et al. 2011). Acritarchs are defined as small microfossils of unknown and probably varied biological affinities. Foraminiferal test linings are organic linings of benthic foraminifera. On the other hand, Scolecodonts are defined as the mouth and body parts of some polychaete worms (primarily marine). Chitinozoa (illustration: plate 8, Fig. 4; Mendonça Filho et al. 2011) is the group characterized by the appearance of flask-shaped hollow bottles (30–2000 µm). It is an extinct group of microfossils found in Palaeozoic marine sediments. Their occurrence has been recorded from the Early Ordovician to Late Devonian.

Structured phytoclasts

The structured phytoclast (ST) is described as well-defined internal structures cellular or non-cellular, thin, unevenly folded, yellowish brown, transparent, or translucent. It includes sub-categories, viz. tubes/filaments (T/F), poorly (PW) and well-preserved woody (W) remains (brown translucent, elongated elements and tracheids), transparent lignocellulosic fragments (TLF), cuticles (CT), plant tissues (PT) and gelified phytoclasts (GP).

- (a) Tubes and filaments (T/F) are recognized by the variable size of structured, unstructured, filamentous, unbranched/branched tubes (Fig. 3c–d), either of algal/fungi (septate/aseptate) or vascular origin has been considered under this subgroup. This subgroup is continental, mainly in origin.
- (b) Poorly preserved woods (PW; Fig. 3e) are the bright brown–orange and elongated structureless remains. Woods (W) are the organic matter with a lath-shaped/blocky outline, changeable from pale yellow to brown/dark brown (Fig. 3f), with cellular structure, partially/clearly visible.
- (c) Transparent lignocellulosic fragments (TLF) are characterized by the secondary xylem (cellular structures of wood) and the grey, light brown, or black colour of the lignin (Fig. 3g–h). The lack of fluorescence, low

Table 1 Classification of dispersed organic matter/sedimentary organic matter (modified after Tyson 1995; Batten 1996; Mendonça Filho et al. 2002, 2011; Oboh-Ikuenobe and Villers 2003; Carvalho et al. 2006; Ercegovac and Kostić, 2006; Zhang et al. 2015; Aggarwal et al. 2019a, b, c; Mays et al. 2021)

Group	Subgroup	Categories	Description	Habitat
Palynomorphs	Sporomorphs	spores	Terrestrial palynomorph produced by Pteridophyte, Bryophyte and fungi (fungal spores). Triangular or circular form with trilete (Y) or monolete (scar) mark	Continental
		Pollen grains	Terrestrial palynomorph are produced by gymnosperm plants. Pollen grains include monosaccates, non-striate bisaccates, striate bisaccates, taeniate, preaccolpates and costate grains. Palynomorphs with varied ornamentation	
	Phytoplankton	Chlorococcale algae	Exclusively colonial algae (<i>Botryococcus</i> and <i>Pediastrum</i>)	Fresh to brackish water
		Dinoflagellate cysts	Resting cysts produced during the sexual part of the life cycle of Class Dinophyceae survives	Mostly marine
		Prasinophytes	Fossilizing structures produced by small quadriflagellate algae (Division Pyrrophyta). Most, like Tasmanites, are spherical; diameter 50–2000 µm, smooth and thick-walled	brackish to freshwater
	Zoomorphs	Acritarchs	Small microfossils of unknown and probably varied biological affinities	Mostly marine
		Foraminiferal test linings	Organic linings of benthic foraminifera	Marine
		Scolecodonts	Mouth and body parts of some polychaete worms	Mostly marine
		Chitinozoa	Flask-shaped hollow bottles (30–2000 µm). It is an extinct group of microfossils found in Palaeozoic marine sediments	Marine
	Zooclast group		It includes graptolites, crustacean eggs, tintinnids, insect cuticle fragments, and other arthropod cuticle fragments	
Structured phytoclast	Tubules/filaments (T/F)		Variable size of structured, unstructured, filamentous, unbranched/branched tubes, either of algal/fungi (septate/aseptate) or vascular origin has been considered under this category	Mostly Continental

Table 1 (continued)

Group	Subgroup	Categories	Description	Habitat
Opaque phytoclast	Wood (W)		Organic matter with a lath-shaped/blocky outline, changeable from pale yellow to brown/dark brown in colour, with cellular structure, partially/clearly visible has been considered under this category	Continental
	Poorly preserved wood (PW)		These are bright brown–orange, elongated structureless remains	
	transparent ligno-cellulosic fragments (TLF)		The TLF are characterized by typical cellular structures of wood (secondary xylem) and the grey, light brown, or black colour of the lignin. The lack of fluorescence, high translucency, and low lignification are important characteristics of the TLF	Continental
	Cuticle (CT)		Protective epidermal cells of higher plants leaves, shoots aerial plant organs, often pale yellow to pale brown/dark brown in colour, thin, rounded or polygonal-shaped cells has been included under this category	
	Plant tissues (PT)		Category includes cellular structures excluding cuticles and wood mainly attributed to parenchyma and herbaceous plants	
	Gelified phytoclast (GP)		Probably results from the higher biodegradation and stronger weathering of leaf remains	
Opaque phytoclast	Structured charcoal (SC)		Opaque and black particles with noticeable structure are incorporated (mainly tracheidial structures)	Continental
	Non-structured charcoal (NSC)		Opaque and black particles without noticeable structure are incorporated	
Degraded Organic matter	Degraded terrestrial (DT)		Degraded structured terrestrial organic matter is formed as an effect of fungal and bacterial activities. Fungi act as the most visible degrading agents which transforms vegetal parts into various organic types with the help of biochemical mechanisms. Various states of preservation partial to completely degraded has been observed in this category	Continental

Table 1 (continued)

Group	Subgroup	Categories	Description	Habitat
	Amorphous organic matter (AOM)		Derived from phytoplankton or by the action of fungi/bacteria on partially biodegraded organic matter convert them into totally structureless amorphous mass. Such amorphous matter looks to be porous and spongy (ranging from partial to complete degradation)	
		Granular AOM	The granular form is mainly yellow to brown under natural light and exhibits irregular aggregated shapes formed by fibrous and ultra microscopic organic particles (< 3 µm)	Marine
		Gelified AOM	Gelified AOM, which is orange to brown and sometimes contains internal structures. The gelified AOM appeared to form clumpy masses with angular sharp shapes	Continental
	Resins		Derived from higher plants of tropical and subtropical forest. Structureless particle, hyaline, homogeneous, fluorescent, rounded, sharp to diffuse outline	Continental

lignification, and high translucency are the essential characteristics of the TLF.

- (d) Cuticles (CT; Fig. 3, Fig. 3i–j) are the protective epidermal cells of higher plant leaves, shoots aerial plant organs, often pale yellow to pale brown/dark brown in colour, thin, rounded, or polygonal-shaped cells.
- (e) Plant tissues (PT) include cellular structures excluding cuticles and wood mainly attributed to parenchyma and herbaceous plants.
- (f) Gelified phytoclast (GP) is the new subgroup of the phytoclasts that many researchers recently introduced (Sebag et al. 2006; Graz et al. 2010; Țabără et al. 2015). After experimental examination, it has been concluded that these are the parts of the fossilized leaf that probably result from the higher biodegradation and more substantial weathering of small GP debris than the large leaf fossils preserved well (Zhang et al. 2015). As a result of which GP is ubiquitous in the palynofacies assemblages.

Woods, transparent lignocellulosic fragments, cuticles, plant tissues, and gelified phytoclast are exclusively continental in origin.

Opaque phytoclasts

Opaque phytoclasts have no visible structure and appear to be homogeneous. These include black-coloured organic matter that showed blade/equidimensional/angular-shaped palynodebris with irregular shapes under the light microscope. Opaque phytoclasts (Fig. 3k) are included in the inertinitic maceral group (mainly fusinite and inertinite). The opaque black phytoclasts comprise carbonized brownish black/oxidized to black-coloured woody tissues, including tracheids. These are further divided into two subgroups: a) structured charcoal (SC) and b) non-structured charcoal (NSC). SC is defined by the opaque and black particles with the noticeable structure are incorporated (mainly tracheidial structures). NSC (Fig. 3k) is described as opaque and black particles without noticeable structures.

Degraded organic matter (DOM)

This group is divided into three subgroups: (a) degraded terrestrial (DT), (b) amorphous organic matter (AOM), and (c) resins.

◀**Fig. 2** **a** An overview of the dispersed organic matter in slide (4x), **b** an overview of the dispersed organic matter in slide (10x), **c** trilete spore (sporomorphs, 40x), **d** trilete spore (sporomorphs, 40x), **e** fungal spore (40x), **f** fungal spore (40x), **g** monosaccate pollen grain (sporomorphs, 40x), **h** non-striate bisaccate pollen grain (sporomorphs, 40x), **i** striate bisaccate pollen grain (sporomorphs, 40x), **j** striate bisaccates pollen grain (sporomorphs, 40x), **k** taeniate pollen grain (sporomorphs, 40x), **l** taeniate pollen grain (sporomorphs, 40x), **m** monolete grain (sporomorphs, 40x), **n** alete grain (sporomorphs, 40x)

- (a) DT is formed as an effect of fungi and bacteria. Fungi are well-known visible degrading agent, which transforms vegetal parts into the different organic types through biochemical mechanisms. Multiple states of preservation partial to completely degraded have been observed (Fig. 3l). It is purely terrestrial in origin.
- (b) AOM (Fig. 3m) is derived from phytoplankton or by the action of fungi/bacteria on partially biodegraded organic matter, which converts them into brown to structureless, porous/spongy, dark or slightly pale amorphous masses/structureless amorphous mass. Such formless matter looks to be porous and spongy (ranging from partial to complete degradation). AOM is further divided into two categories based on their origin (Combaz 1980; Batten 1983; Courtinat et al. 2003; Ercegovic and Kostić 2006; Pacton et al. 2011; Suárez-Ruiz et al. 2012), i.e. marine and continental/terrestrial. Its gelified appearance defines terrestrial AOM, while the granular AOM is produced by the degradation of the phytoplankton with a granular/fluffy appearance (Țabără et al. 2015). Granular AOM with patchy fluorescence (depending on its oxidation state) from marine sources derived from microbial reworking (illustration: Țabără et al. 2015). Its colour varies like in coastal areas its yellow to green in oxic sedimentary conditions, while it is brown in dysoxic/anoxic conditions in pelagic zones (Marson and Pocock 1981; Valdés et al. 2004; Ercegovic and Kostić 2006;). It is mainly yellow to brown under natural light and exhibits irregular aggregated shapes formed by fibrous and ultramicroscopic organic particles (< 3 μm). Gelified AOM (illustration: Țabără et al. 2015) is orange to brown and sometimes contains internal structures (Pacton et al. 2011) derived from terrestrial sources degraded by bacteria, being a secondary microbial product. It appeared to form clumpy masses with sharp angular shapes.
- (c) Resins are derived from higher plants of tropical and subtropical forests. Resins are recognized by structureless particle, hyaline, homogeneous, fluorescent, rounded, sharp to diffuse outlines derived from higher plants, so this category is purely continental in origin.

Palaeoenvironmental interpretations based on the different forms of the dispersed organic matter

Besides providing biostratigraphic ages, various fossil groups and taxa play a significant role in providing palaeoenvironmental information. The palynofacies studies are based on the qualitative (presence/absence of taxa) or quantitative data (ratios between benthonic and planktonic foraminifera; dinoflagellates and spore/pollen, etc.). Some particular taxa are attributed to specific environmental conditions such as salinity (hypo, normal or hyper), anoxia/dysoxia and bathymetry. All organic-walled fossils can be observed in a palynological slide. These slides include several fossil groups (spore, pollen grains, algae, dinoflagellates, foraminiferal test linings, fungal hyphae, acritarchs, etc.) derived from different environments resultantly; it usually allows palaeoenvironmental elucidation. The palynofacies symbolize the primary composition of the organic matter in the sedimentary rock after the long process of organic diagenesis and sedimentation. The composition of organic matter is directly controlled by the palaeoenvironments. Palynofacies uses the relative proportions of several fossil groups for the interpretation of the sedimentation settings, such as land-derived Vs. marine-derived and spores Vs. Acritarchs. The quantity of the organic matter exhibits an exceptional ability to trace palaeoenvironmental evolution under different climatic and sedimentary settings (Carvalho et al. 2006; Sebag et al. 2006; Zhang et al. 2015). Resultantly, palynofacies investigation has been applied as one of the fundamental parameters for palaeoenvironmental interpretation (Buchardt and Nielsen 1991). As the relative proportions of the various organic matter particles reflect oxygenation conditions, this proxy has also been widely applied to estimate the lake-level changes and distances from the lakeshore (Sebag et al. 2006).

Palynomorphs

The Indian Gondwana basins account for about 99% of the coal reserves of the country, which makes the Permian period (252.2–289.9 Ma) economically important. Permian was mainly flourished by various plant groups, viz. conifers, Ginkgophytes, Gnetales, Peltaspermales (seed ferns), Glossopterids, Cycads, Voltzialean, and Cordaites. In the end, Permian, mainly the flora, was dominated by the seed plants (Gradstein and Kerp 2012), but noteworthy extinction of fauna has been documented (Henderson et al. 2012). Instead, numerous Cordaites, Conifers, Glossopterids became extinct, but no major extinction of the plants has been accounted for (Gradstein and Kerp 2012). Seed ferns (Conifers, Ginkgophytes, Gnetales, Peltaspermales) belong

Fig. 3 **a** Dianoflagellate cyst (40x), **b** foraminiferal test lining (10x), **c** fungal hyphae (40x), **d** fungal hyphae (40x), **e** poorly preserved woody material (PW), arrow marked (10x), **f** well-preserved woody material (W), arrow marked (10x), **g** woody tracheid (TLF, 40x), **h**

woody tracheid (TLF, 40x), **i** cuticle (10x), **j** cuticle (20x), **k** opaque phytoclasts (10x), **l** degraded organic matter (DOM, 10x), **m** amorphous organic matter (AOM, 20x), **n** degraded organic matter dominating palynofacies association (10x)

Fig. 4 **a** Lath-shaped opaque phytoclast (10x), **b** lath-shaped translucent phytoclast (20x), **c** lath-shaped phytoclasts dominating palynofacies association (20x), **d** equidimensional opaque phytoclasts (20x), **e** equidimensional phytoclasts dominating palynofacies association (4x)

to higher terrains, so they have been included in upland flora. Cordaites grow on dry land and wet swamps, while Glosspterids (woody gymnosperms) usually grow in wet and swampy habitats. Spores (Filicopsids, Equisetopsids, Lycop-sids) thrive in swampy and marshy settings. Glossopterids grow up in hygrophilous to the mesophilous environments and flourish in flat lowland swamps; on the other hand, conifers were transported from the more distant areas to the palaemire (Knoll and Nicklas 1987; Guy-Olhson 1992; Caz-zulo-Klepzig et al. 2005; Ruckwied et al. 2014). Spores of ferns indicate temperate climate (Götz and Ruckwied 2014). The abundance of arboreal vegetation indicates the landward settings (Ruckwied et al. 2014). The abundant occurrence of saccate (monosaccates, bisaccates, and taeniates) gymnospermous pollen grains (Glossopterids, Coniferales, and Cordaites) along with few spores is widespread in Permian palynoassemblages which suggests temperate climatic conditions (Götz and Ruckwied 2014; Ruckwied et al. 2014).

Bisaccate palynomorphs are very vigorous and can be simply accumulated by the hydrodynamic processes. Additionally, they are commonly dispersed due to their easy transference (wind and water) and buoyancy. Resultantly, these are very frequent in offshore settings. Tree-dominated palaeovegetation (including ferns, cycads, Glossopterid, and Cordaites) suggests broad swamps during the deposition (Wheeler and Götz 2017; Aggarwal et al. 2019a, b, c).

Botryococcus (Carboniferous to recent) is a diversified green alga commonly occurring in different water bodies like lakes, ponds, wet mud, ditches, and bogs (Round 1965; Guy-Olhson 1992). *Botryococcus* belongs to the family *Botryococcaceae*. It is reported to be distributed in broad geographical regions, found in fresh to brackish water conditions (Chisti 1980; Tennant et al. 2019). *Botryococcus* contains unsaturated fatty hydrocarbons and can generate high hydrocarbons (Maxwell et al. 1968; Taylor et al. 2012; Hirose et al. 2013).

The occurrence of prasinophytes algae has been documented in the sediments of the Precambrian to the recent age. These are produced by tiny quadriflagellate phytoplankton. Recent forms occur in freshwater to the hypersaline settings, but fossilized forms are mainly marine (Mendonça Filho et al. 2011). But on the other hand, prasinophytes algae (*Cymatiosphaera*-like cysts) from the Palaeozoic to early Mesozoic (Clausing 1993; Dotzler et al. 2007; Kustatscher et al. 2014) sediments have been reported from brackish to freshwater sediments (Zippi 1998; Mudie et al. 2011; Mays et al. 2021).

Dinoflagellate cysts or dinocysts (division Dinoflagellata) are produced by single-celled red algae classified as Pyr-rhophyta. These are defined as one-celled aquatic organisms bearing two dissimilar flagella and having characteristics of both plants and animals. Mostly the organisms are marine and form an essential part of the marine microphytoplankton,

though some live in freshwater habitats (Masure et al. 2017). These are very common in Upper Triassic to Holocene sediments and act as an excellent biostratigraphic indicator due to their geographical distribution and evolution. Different marine environments can be easily identified based on their morphology and assemblages (Tyson 1995; Vincent 1995).

Acritarchs are organic-walled microfossils that are interpreted as unicellular marine algae (Riegel 2008). Mainly the acritarchs, genera of the Gondwana time, are represented by genera of *Veryhachium*, *Micrhystridium*, *Dictyotidium*, and *Leiosphaeridia*. However, some workers considered *Leiosphaeridia* of freshwater green algae (Mays et al. 2021). These acritarchs probably represent stress-tolerant phytoplankton (Luo et al. 2013; Rampino and Eshet 2018). These are the excellent biostratigraphic indicators in the Palaeozoic (most diverse during the Ordovician–Silurian) but less important in Mesozoic and Cenozoic sediments. The organisms which produced these palynomorphs are either extinct or unknown, and these have been classified exclusively based on morphological characteristics.

Foraminifers are defined as single-celled organisms, members of the class of amoeboid protists. These are tectinous linings derived from certain marine benthic foraminifera. The external shell is called a test which is made up of diverse forms and materials. A test can have either one or multiple chambers. Most of the foraminifera are marine. The majority of them are benthic, while very few are planktonic. Fossilized linings are mainly produced by benthic foraminifers and predominated by the planispiral foraminifers (Tyson 1989, 1995). They are known as excellent markers of marine or brackish marine shelf conditions (Tschudy 1969; Tyson 1993, 1995).

Scolecodonts are represented as mouth and body parts of some polychaete worms, which are primarily marine in nature (Tyson 1995). The most abundant occurrence has been recorded during the Ordovician to Devonian while the geologically ranges from the early Ordovician to recent sediments.

Chitinozoans are flask-shaped extinct marine organic-walled microfossils that occur in rocks of the Palaeozoic (Ordovician to Devonian) age. However, they are of uncertain affinity but may be considered as the eggs of marine metazoans. Due to their restricted geological occurrence, these organisms are considered excellent biostratigraphic indexes, useful palaeoenvironmental markers, and thermal maturity indices. Due to the thermal alteration, the test changes from translucent and amber colour to brown and finally black/opaque (Tyson 1995).

Another group known as zooclast group comprises animal-derived organic particles (graptolites, crustacean eggs, tintinnids, insect cuticle fragments, arthropod cuticle fragments, etc.). These are materials of definite animal origin having specific morphological characteristics. The most

common varieties of zooclasts include organic linings from some bivalve shells and ostracod carapaces, arthropod exoskeletal debris, and graptolite fragments (Tyson 1989, 1995).

Structured organic matter

Terrestrially derived structured organic matter, mainly including the woody material, cuticles, biostructured organic matter, are mainly related to the deltaic fronts and proximal settings (Marson and Pocock 1981; Tyson 1995; Ercegovac et al. 1997; Peters et al. 2003). This group of organic matter represents the oxidizing conditions. Cuticles are derived from the leaves, which are considered to be the most buoyant type of structured organic matter cuticles deposited from the suspended load when the energy conditions are shallow. These are found in high percentages in deltaic distributary and prodeltaic facies (Parry et al. 1981; Tyson 1993; Vincent 1995). The abundant occurrence of the lath-shaped woody particles represents (Fig. 4a–b) the short transportation of the sediments (Carvalho et al. 2013; Aggarwal et al. 2019a, b, c). Structured organic matter particles commonly occur in delta-fronts, prodelta, lagoons, and prodelta settings (Marson and Pocock 1981; Ercegovac et al. 1997). On the other hand, they are rare to common in lake and intertidal sedimentary environments and are absent to rare in beach mudflats (Ercegovac and Kostić 2006). Small-sized phytoclast particles represent the distal deposition and vice versa (Tyson and Follows 2000). On the other hand, the abundance of the equidimensional phytoclasts (Fig. 4c) in the sediments represents the variable energy conditions for the deposition of the sediments (Aggarwal et al. 2019a; b, c). In general, the percentage of phytoclasts decreases in the distal direction and is strongly affected by the proximity to the source, granulometric composition of the sediments, and fragmentation through sample preparation (Tyson 1993; Vincent 1995; Mendonça Filho 1999).

Opaque phytoclasts

The opaque black phytoclasts are mainly derived from the oxidation of the structured phytoclasts (chiefly woody particles) during prolonged transport or post-depositional distinctions through usual or higher temperatures (Closas et al. 2005; Cincotta et al. 2015). The abundant occurrence of opaque black phytoclasts specifies highly oxidizing environments and degradation of terrestrial organic matter or proximity to terrestrial sources (Tyson 1989; Carvalho et al. 2013). The massive amount of opaque black phytoclasts accompanied by the low quantity of the other organic matter types has been recognized in oxic swamps,

delta-fronts, prodelta, etc. (Marson and Pocock 1981; Clo-sas et al. 2005; Pieńkowski and Waksmundzka 2009) and primarily associated to the proximal side of the deposition (Carvalho et al. 2013) of the organic matter (Tyson 1989; Cincotta et al. 2015). The presence of many structured opaque phytoclasts may represent palaeofire evidence (Scott and Glasspool 2007; Kumar et al. 2011; Brown et al. 2012; Glasspool and Scott 2013). Opaque phytoclasts are frequently predominant in high-energy environmental settings, such as delta-fronts, prodelta, and near-shore habitats (Pieńkowski and Waksmundzka 2009), due to its inertness nature. The presence of opaque phytoclasts accompanied by a little amount of the palynomorphs and other types of organic matter, possibly replicate flooding events in the oxic environment. Consequently, the occurrence of the opaque phytoclasts is usually found towards the proximity to the inland source or its redeposition of the organic matter from the fluvio-deltaic fronts (Tyson 1989; Cincotta et al. 2015; Aggarwal et al. 2019a, b, c). Additionally, it may be concluded that flooding may have been occurred due to the higher terrestrial input because of the high impounding of the water due to fluvial activity. The presence of the equidimensional opaque phytoclasts (Fig. 4d–e) reflects the deposition of the sediment under the relatively high- to moderate-energy-level conditions (Wheeler and Götz 2016, 2017). These particles are prevalent in coarse-grained, high-energy environments (distributary channel sands and point bars) (Denison and Fowler 1980; Parry et al. 1981; Batten 1982a, 1982b; Bustin 1988; Tyson 1989, 1993, 1995).

Degraded organic matter

Degraded organic matter particles are the resultant of the oxidized structured/translucent phytoclasts (mainly woods, woody material, cuticles, and plant tissues). The degraded organic matter has been recorded in low-energy settings like waterlogged/standing water column/flooded palaeomires/peat swamps/lakeshores (Tyson 1993; Zhang et al. 2010; Peters et al. 2013; Aggarwal et al. 2019a, b, c). It is purely continental.

The organic component, which appears structureless, refers to the AOM under light microscopy in palynological slides, including bacterially and phytoplankton-derived organic matter, higher plant resins, and amorphous products macrophyte tissue diagenesis (Tyson 1993, 1995). The high percentage of AOM is also assumed as a result of the preservation of benthic microbes or autochthonous planktonic organic matter or eradication of the distal palaeodepositional setting of the dynamic sources of diluent terrestrial organic matter (Tyson 1993, 1995; Mendonça Filho et al. 2010; Pacton et al. 2011) in the sluggish and oxygen-depleted water conditions (Bryant et al. 1988). The predominance of

AOM can be inferred as dysoxic/anoxic (reducing environment) conditions in low-energy settings. Oxygen content is one of the most critical parameters for the preservation of degraded OM and the AOM (Pacton et al. 2011). He suggested that anoxia stimulates an advanced darkening due to polymerization, which can be inferred that AOM has been deposited under anoxic conditions. Granular AOM has been considered marine in origin, while gelified AOM is purely continental.

Palaeoenvironmental analysis

Marine deposits

The APP (AOM–Phytoclasts–Palynomorphs) ternary plot (Fig. 5) after Tyson (1993, 1995) has been widely applied to understand the palaeodepositional environment and the transport pathways of the organic matter in shallow and deep-sea depositional settings. It correlates the percentage of the three main groups of organic matter identified under white transmitted light, and based on it, palynofacies assemblages are formed (Mendonça Filho et al. 2011). In the ternary diagram, the most proximal components (phytoclasts) are used to put on the top of the ternary diagram. The components that belong to the most reducing conditions (AOM) are placed on the bottom left corner of the diagram. The plot can trace the relative proximity to the source of the terrestrial organic matter particles, transportation pathways, and reducing conditions of the depositional sub-environments, which denotes AOM preservation. The top to the base of the diagram represents the proximal–distal trend, while left to right represents the change from the reducing to the oxidizing (redox) settings. As in the marine ecosystems, more than 60% of the occurrence of the palynomorphs are sporadic and dominated by AOM, so in most cases, the lower right corner of the diagram is usually empty. Based on the palynofacies components and their assemblages, nine distinct environments (I–IX) have been identified in marine settings using the three main organic matter types. These nine environments are range from a highly proximal shelf or basin environment to a distal shelf or basin environment. The top of the diagram shows the shallowest sediments and are generally both proximal (high phytoclast supply) and oxic. If the basin is oxic, then most of the area of the ternary diagram would be covered by the phytoclasts due to the abundance of the opaque phytoclasts and the structured organic matter particles, resultantly the left basal portion of the ternary would be not be filled due to the least presence of AOM. If AOM is predominant in any succession, then it does not mean that the particular rock would be oil-prone, for that fluorescence of AOM has to be checked (Mendonça Filho et al. 2011).

Fig. 5 APP (AOM–Phytoclasts–Palynomorphs) ternary plot after Tyson (1995)

Table 2 shows a key to marine palynofacies fields recognized on the APP diagram according to Tyson (1993, 1995).

Beside APP diagram some other ternary diagram has also been defined to better resolve the results for the palaeodepositional settings. Some examples of other ternary diagrams are SPP (spore–microplankton–pollen grain), DSA (dinocyst–sporomorph–acritarch), PAD (prasinophytes–acritarch–dinocyst), GPG (gonyalacoid–peridinioid–other gonyalacoid), APB (AOM–*Pediastrum*–*Botryococcus*), etc. (Mendonça Filho et al. 2011).

Continental deposits

For the continental set-up, various workers have used the modified ternary models like the ternary diagram proposed by Hacquebard and Donaldson (1969) and modified by Marchionni (1980) and Singh and Singh (1996); later, it was modified by Aggarwal et al. 2019a, b, c. The ternary plot (Fig. 6) has been modified as SP-ST + DT-AOM + CH, where SP stands for spore–pollen or continental palynomorphs including fungal spores, ST stands for structured organic matter, DT stands for degraded organic matter, AOM stands for amorphous organic matter, and CH stands for the opaque phytoclasts. Based on the predominance of the various forms of organic matter, three distinctive environments have been described as forest swamps, lake shores/flooded palaeomire, and oxidized swamps. Similarly, palaeoenvironmental interpretation of the Yanchang Formation

for the continental deposits has been proposed by Zhang et al. 2015. The ternary plot was represented by AOM-TLF + OP-GP + cuticles + palynomorphs (AOM-TO-GCP). AOM is defined as amorphous organic matter, TLF has been described as transparent lignocellulosic fragments, OP is opaque phytoclasts and GP is as gelified particles. Based on these various forms, three different environments have been interpreted as distal dysoxic–anoxic deep basin, shelf-to-basin transition, and proximal sub-oxic shelf.

Besides it, some of the previous workers (Smyth 1979; Goodarzi 1985; Diessel 1986; Mukhopadhyay 1986; Mishra and Cook 1992) have also studied the palaeoenvironmental depositional settings based on the analysis of the coal petrology.

Discussion

Palynofacies is the tool that can be easily applied in the various fields of geology like to recognize the proximal–distal relationships with respect to source, depositional polarity (i.e. onshore–offshore), regressive–transgressive trends in stratigraphic sequences, hydrocarbon source rock potential, in the identification of the various environments (oxic open marine, dysoxic–anoxic marine, and brackish freshwater, flooded palaeomire, swamps, peats, etc.).

Table 2 Various depositional set-ups in the marine/seashore environments proposed by Tyson (1995)

S.N	Environment	Comments	Spore: bisaccates	Microplankton	Kerogen type
I	Highly proximal shelf basin	High phytoclast supply dilutes all other components	Usually high	Very low	III, gas-prone
II	Marginal dysoxic–anoxic basin	AOM diluted by high phytoclast input, but AOM preservation moderate to good. Amount of marine TOC dependent on basin redox state and dilution	High	Very low	III, gas-prone
III	Heterolithic oxic shelf ('proximal shelf')	Generally low AOM preservation; absolute phytoclast abundance dependent on actual proximity to the fluvio-deltaic source. Oxidation and reworking common	High	Common to abundant dinocyst dominant	III or IV, gas-prone
IV	Shelf-to-basin transition	Passage from shelf to basin in time (e.g. increased subsidence/water depth) or space (e.g. basin slope). Absolute phytoclast abundance depends on proximity to source and -degree of redeposition. The amount of marine TOC depends on basin redox state. IVa dysoxic–sub-oxic, IVb sub-oxic–anoxic	Moderate to high	Very low low	III or II, mainly gas-prone
V	Mud dominated oxic shelf (distal shelf)	Low to moderate AOM (usually degraded). Palynomorphs abundant. Light-coloured bioturbated, calcareous mudstones are typical	Usually low	Common to abundant dinocysts dominant	III > IV, gas-prone
VI	Proximal sub-oxic–anoxic shelf	High AOM preservation due to reducing basin conditions. Absolute phytoclast content may be moderate to high due to turbiditic input and/or general proximity to the source	Variable low to moderate	low to common dinocysts dominant	II > oil-prone
VII	Distal dysoxic–anoxic shelf	Moderate to good AOM preservation. Low to moderate palynomorphs. Dark-coloured slightly bioturbated, calcareous mudstones are typical	Low	Moderate to common Dinocysts dominant	II > oil-prone
VIII	Distal dysoxic–oxic shelf	AOM-dominated assemblages, excellent AOM preservation. Low to moderate palynomorphs (partly due to masking). Typical of organic-rich shales deposited under stratified shelf sea conditions	Low	Low to moderate dinocysts dominant, % prasinophyte increasing	II > I, oil-prone
IX	Distal sub-oxic–anoxic shelf	AOM-dominated assemblages, low abundance of palynomorphs partly due to masking. Frequently algininate-rich. Deep basin or stratified shelf sea deposits, especially sediment starved basins	Low	Generally low Prasinophytes often dominant	II > I, highly oil-prone

Fig. 6 Ternary diagram proposed by Hacquebard and Donaldson (1969) and modified by Marchionni 1980; Singh and Singh 1996; Aggarwal et al 2019a, b, c

Palynofacies characterization for the interpretation of palaeodepositional settings along with the proximal and distal trend of the sedimentary rock

Palynofacies used in the field of the palaeodepositional settings is one of the well-known and widely accepted tools for the reconstruction of the palaeoclimate (Obok-Ikuenobe and Villier 2003; Schiøler et al. 2010; Mendonça Filho et al. 2011; Carvalho et al. 2013; Aggarwal et al. 2019a, b, c) not only in the older deposits but also in the recent sediments. It is very easy to identify the proximal and distal trend of any succession with the help of the various morphographical features (size sorting, degradation, oxidation, etc.) of the different types of organic matter particles. Generally, the coarser sediment used to be deposited towards the proximal side in high-energy conditions (higher silt and sand content).

The proximal and distal trend in any sequence can be more precisely explained with the help of the Phytoclast Preservation Index (PPI), which directly explains from the proximal to the distal by the increasing oxidation and degradation of the phytoclasts and decreasing trend of the preservation (Tyson 1993, 1995; Vincent 1995; Mendonça Filho 1999; Mendonça Filho et al. 2011). It denotes that the opaque phytoclasts are dominant at the distal end while the structured organic matter is dominant at the proximal end. Besides it, the proximal–distal concept and the parameters calculated for the groups and subgroups of the different organic matter components have been described by many authors (Tyson 1993, 1995; Vincent 1995; Mendonça Filho 1999) in detail (see table 12 Mendonça Filho et al. 2011).

Palynofacies characterization for hydrocarbon source rock

Sediments which are having the ability to generate petroleum are called ‘source rocks’. Organic-rich shales, very fine-grained carbonates, mudstones, and oxygen-deficient waters are considered excellent source sediments. Palynofacies is considered very significant while evaluating source rock potential. Palynofacies is classified into various categories depending on the degree of alteration (Marson and Pocock 1981). Detailed classification is summarized in Table 1; Thakur and Dogra 2011. Structured organic matter contributes to gaseous hydrocarbons, and degraded organic matter (plant-derived organic matter that has undergone biodegradation but still shows visual traces of its cellular structure) is considered to possess a better hydrocarbon source potential than structured organic matter. Amorphous organic matter is considered an excellent source for liquid hydrocarbons; spore–pollens are rich in lipids known for their contribution to the liquid hydrocarbon. Opaque phytoclasts have negligible hydrocarbon source rock potential except for dry gas. Resultantly, the dominance and the sub-dominance of the various forms of the organic matter types also indicate the source rock potential of any rock. Concurrence of TAI (Thermal Alteration Index) with palynofacies is an excellent parameter for the source rock evaluation and has been used widely by different researchers (Misra and Pundeer 1994; Thakur and Dogra 2011; El Atfy et al. 2014; Peters et al. 2015; Christoph et al. 2019).

The implication of palynofacies in high-resolution sequence biostratigraphy:

This field has emerged as an efficient tool for the identification of the sequence boundaries (lowstand system tracts: LST, transgressive system tracts: TST, high-stand system tracts: HST, MFS: maximum flooding surface, SB: sequence boundaries) with the concurrence of the palynomorphs and lithofacies (Batten and Stead 2005). Conceptual models for palynofacies in sequence stratigraphy based on the distribution of the kerogen were proposed by many researchers (Steffen and Gorin 1993; Tyson 1995; Hart et al. 1994; Carvalho et al. 2006). The spatial and stratigraphic variations in the distribution of sedimentary organic matter reflect changes in the depositional system related to relative sea-level fluctuations. LSTs are generally defined by the predominance occurrence of the large phytoclasts, poorly preserved numerous pollen grains, and spores (partially oxidized). Opaque phytoclasts are the common components of such palynofacies. On the other hand, the palynofacies associated with TSTs are predominated by the occurrence of the dinoflagellate cysts and other marine components. At the same time, miospores and phytoclasts are smaller and less varied. HSTs are symbolized as the assemblage represented as AOM as a significant content along with marine components (dinoflagellate cysts as most numerous palynomorphs). Resultantly, palynofacies analysis along with some integrated proxies (lithofacies and geochemical aspects) may be used as a powerful tool for high-resolution sequence biostratigraphy. The different workers have used this in various successions (Jaramillo and Obboh-Ikuenobe 1999; Holz et al. 2002; Vallejo et al. 2002; Gotz et al. 2003; Dybkjær 2004; Obboh-Ikuenobe et al. 2005; Ruf et al. 2005; Carvalho et al. 2006; Prasad et al. 2013; Davtalab et al. 2017).

Conclusion

- (1) The study has its limitations. Accurate identification and observation of the different forms of the organic matter types in the palynological material are required for the successful implication of palynofacies studies in various aspects.
- (2) The observation of the different forms of the organic matter types following the change in the lithological patterns through the stratigraphic succession and tagging of the lithofacies as well as the palynofacies is highly recommended for the more acceptable resolution and the better understanding of the palaeodepositional set-up, source rock potential for petroleum and complete information of the stratigraphy.

- (3) Recognition of different forms of the organic matter types in conjunction with the biostratigraphy can be employed as an efficient tool in identifying the various sequence boundaries in succession with the absence of the apparent sedimentological evidence.
- (4) The study is also helpful in guiding the well trajectory during drilling for the discrimination between non-pay zones above, below, and within reservoirs.

Acknowledgements The author expresses her sincere thanks to the director of BSIP, Dr. Vandana Prasad, for permission to publish the paper and for her continuous encouragement. The author is also thankful to the anonymous reviewers for their valuable suggestions to improve the quality of this MS.

Funding The author received no external funding for this research work.

Declarations

Conflict of interest The author declares that she has no conflict of interest.

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